The Effects of Field Line Curvature (FLC) Scattering on Ring Current Dynamics and Isotropic Boundary

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Abstract In the ring current dynamics, various loss mechanisms contribute to the ring current decay, including losses to the upper atmosphere through particle precipitation. This study implements the field line curvature (FLC) scattering mechanism in a kinetic ring current model and investigates its role in precipitating ions into the ionosphere during the 17 March 2013 storm. Simulation results indicate that (1) the FLC scattering process exerts on energetic ions on the nightside where the magnetospheric configuration is more stretching. It is more effective on heavy ions (e.g., O⁺). These ion losses thereafter lead to a faster recovery of the ring current. (2) The FLC-associated ion precipitation mainly occurs in the outer region (L > 5 for protons and L > 4.5 for oxygen ions) on the nightside. The O⁺ precipitation takes places in a wider region than protons although its intensity is much lower. Comparisons with POES observations suggest that more proton precipitation is needed in the inner region. This is probably caused by the less stretched configuration in the simulation that prevents more precipitation. It may also imply that other loss process is required in the model such as wave-particle interactions. (3) The storm time precipitating proton flux of tens of keV due to the FLC scattering sometimes becomes comparable to that of electrons on the nightside, although electrons usually dominate the ionospheric energy deposition from the midnight eastward toward the dayside. (4) The FLC scattering process seems to be capable of explaining the formation of isotropic boundary in the ionosphere during the investigated event.

1. Introduction

It is generally understood that the Earth’s ring current is composed of both electron and ion species, mainly H⁺, He⁺, and O⁺. The energy content of the ring current during storm time is dominantly from these ion species. Therefore ion loss processes can influence the intensity of the ring current while competing with energization processes. Ions can be supplied from the tail plasma sheet into the inner magnetosphere by convective electric field, gaining energies adiabatically. They drift around the Earth due to magnetic gradient and curvature effects. Along their pathways, the ring current ions can be lost via charge exchange with neutral hydrogen when they encounter the geocorona (Dessler & Parker, 1959) and become neutralized. They can also lose energy and be scattered by the plasmaspheric ions and electrons due to Coulomb collision when they move through the ambient thermal plasma (Jordanova et al., 1996).

Of importance for the ring current decay are two additional collisionless scattering mechanisms, which may have significant impact on the ring current dynamics: wave-particle interactions and field line curvature (FLC) scattering. Electromagnetic ion cyclotron (EMIC) waves can resonate with energetic ring current ions once the wave frequency satisfies the resonance condition. While this process depends on the wave intensity and location, the FLC scattering is controlled by the geometry of magnetic field lines and occurs where the FLC radius is comparable to the gyroradius of particles (Büchner & Zelenyi, 1989; Delcourt et al., 1996; Lyons & Speiser, 1982; Sergeev et al., 1983, 1993; Tsyganenko, 1982), thus resulting in chaotic motion of the particles. Due to the much smaller gyroradius of electrons, the FLC scattering loss is more efficient on ions with the same energy. Stretched magnetic field lines possess smaller curvature radius and therefore are more applicable for FLC scattering. Such condition often appears near the equatorial current sheet on the nightside, and FLC scattering is also named as current sheet scattering. Ebihara et al. (2011) examined the decay of ring current due to FLC scattering and found that the ring current shows rapid recovery with an e-folding time of 6 hr when the FLC scattering is included, as opposed to a e-folding time of 12 hr when it is excluded. Their study assumed that the FLC scattering works on protons only while its impact on other ion species was not considered. However, it is known that the oxygen ion flux could sometimes exceed the...
protons and are of the same importance to the ring current growth during geomagnetic disturbed time (Daglis, 1997; Daglis & Axford, 1996; Fernandes et al., 2017; Yue et al., 2019) and that the oxygen ion is more effectively influenced by the FLC scattering because of its larger gyroradius; therefore, the contribution of O\(^+\) precipitation may not be negligible. The study of Ebihara et al. (2011) thus provided a lower limit of the rapid decay of the ring current due to FLC scattering mechanism.

Besides the impact on the ring current dynamics, the FLC scattering process is believed to be associated with the formation of isotropic boundary (IB) (Dubyagin et al., 2018; Ganushkina et al., 2005; Meurant et al., 2007; Sergeev & Gvozdevsky, 1995; Sergeev et al., 1993), a region in the auroral zone where the precipitating flux changes abruptly. Equatorward of the IB, the trapped particle flux is much higher than the precipitating flux, while the two are comparable poleward of the IB. In other words, the loss cones are filled up at higher latitudes whereas they are empty at lower latitudes of the IB. This boundary is identified in many observations as the low-Earth orbit satellites (e.g., DMSP and NOAA/POES) travel across it (Dubyagin et al., 2018; Newell et al., 1998). Such a boundary characterizes a transition from weak precipitation to strong isotropic precipitation at higher latitudes and maps to the magnetosphere location across which the rate of pitch angle scattering varies greatly. Recently, studies have debated on the mechanisms of strong pitch angle scattering responsible for the isotropic proton precipitation on the nightside (see Dubyagin et al., 2018) and have questioned the traditional IB mechanism, that is, FLC scattering process, proposed by Sergeev et al. (1993). For example, Liang et al. (2014) found reversed type of energy-latitude precipitation boundary, which cannot be explained by the FLC scattering but is EMIC wave driven. Sergeev et al. (2015) found multiple dropouts of precipitated-to-trapped flux ratio (an indication of IB) near the IB location and newly emerging isotropic precipitation equatorward of the previous IB. These are hard to explain with a simple FLC-based model. Dubyagin et al. (2013) found the anomalous IB dispersion statistically appearing in the dusk sector where EMIC waves occurrence peaks in main phase (Jordanova et al., 2007, 2012). These studies show that other mechanisms, probably the EMIC wave scattering, may be responsible for the formation of IB. However, exactly which mechanism is the reason for the proton precipitation near the IB location is still under discussion (Dubyagin et al., 2018; Liang et al., 2014; Sergeev et al., 2015).

Resulting from the ring current ion scattering loss, protons precipitate down to the upper atmosphere, subsequently generating proton auroras. They are typically observed in two spatial regions, as firstly mentioned in Søraas et al. (1977), with one at high latitudes, corresponding to proton auroral oval and the other one at subauroral region, separated from the high-latitude electron and proton auroral ovals. Previous studies have found close association between subauroral proton precipitation with EMIC waves in different locations (see review by Frey, 2007; Yahnin & Yahhina, 2007), such as dayside proton flashes (Fuselier et al., 2004; Hubert et al., 2003) and afternoon/nightside detached proton arcs (e.g., Immel et al., 2002; Jordanova et al., 2007; Nishimura et al., 2014; Spasojevic et al., 2004; Spasojevic & Fuselier, 2009). The EMIC wave-driven proton precipitation could occur in localized regions where the local plasma conditions meet instability threshold and excite EMIC waves (e.g., Jordanova et al., 1997). Such locations can be spotty or elongated, as inferred from the auroral images. On the other hand, the FLC scattering-driven proton precipitation may take place over a much wider region if the nightside magnetic field lines are sufficiently stretched in a global scale. With the proton precipitation, one can monitor the degree of magnetic field stretching in the magnetotail and further help understand the magnetic mapping. Liang et al. (2013) proposed a technique to derive the magnetic FLC with in situ measurements and determine the precipitating proton fluxes in order to obtain the mapping between the magnetosphere and ionosphere. Their study excluded the effects of EMIC waves on the precipitation by selecting events without EMIC activities. While it is highly possible that the proton precipitation led by EMIC-proton interactions and that due to FLC scattering coexists, the assessment on the role of both mechanisms is required in order to achieve better understanding of the proton auroral dynamics. However, compared to extensive studies on the association of proton aurora precipitation with EMIC waves (e.g., L. Chen et al. 2014; Fuselier et al., 2004; Jordanova et al., 2007; Nishimura et al., 2014; Spasojevic et al., 2004; Spasojevic & Fuselier, 2009; Yahnin & Yahnina, 2007; Yahnina & Yahnin, 2014), the investigation on the association with the FLC scattering is still lacking.

Recently, M. W. Chen et al. (2019) included the FLC scattering mechanism in their RCM-E ring current model and compared the electron and ion precipitating flux and their respective effects on the ionospheric electrodynamics. They found that the FLC-associated ion scattering contributes much less to the precipitating energy flux, and thus the resultant conductance of the ion aurora is far smaller than that of electron
aurora. They used a simplified model for the FLC scattering loss rate, independent of pitch angles. In this study, we also investigate the effect of FLC scattering on the ionospheric ion precipitation, as well as on the ring current decay. However, unlike M. W. Chen et al. (2019), we implement the FLC scattering mechanism in the RAM-SCB ring current model as a diffusion process by using related diffusion coefficients that are energy and pitch angle dependent. We simulate the 17 March 2013 storm event to understand the role of FLC scattering in changing the ring current dynamics, the global pattern of precipitation, and the IB positions. Section 2 describes the model and the implemented FLC scattering loss mechanism. Section 3 presents simulation results on the morphology of ion precipitation associated with the FLC scattering, the subsequent effects on the ring current decay and ionospheric precipitation, as well as the relationship with the IB. Section 4 summarizes this study.

2. Model Description

The kinetic ring current model used to study the role of FLC scattering is the ring current-atmosphere interactions model (RAM) coupled with a self-consistent (SC) magnetic field (B) and electric field code (Jordanova et al., 2006, 2010; Yu et al., 2017; Zaharia et al., 2006). This RAM-SCB model solves the bounce-averaged Fokker-Planck equation of distribution functions \( F_l(t) \) for three ring current ion species (\( H^+ \), \( He^+ \), \( O^+ \)) and electrons:

\[
\frac{\partial F_l(t, R, \phi, E, \alpha)}{\partial t} + 1 \frac{\partial}{R^2 \partial R} \left( R^2 \frac{dR}{dt} > F_l \right) + 1 \frac{\partial}{\partial \phi} \left( E < \frac{d\phi}{dt} > F_l \right) + \frac{1}{yp\Delta E} \left( yp < \frac{dE}{dt} > F_l \right) + 1 \frac{\partial}{\partial \mu_o} \left( h\mu_o < \frac{d\mu_o}{dt} > F_l \right) = \langle \frac{\partial F_l}{\partial t} \rangle_{\text{loss}} \tag{1} \]

where the distribution function \( F_l \) is solved in the magnetic equatorial plane within a radial distance of \( 2.0 < R < 6.5 \ Re \), covering all magnetic local times \( \phi \), pitch angles \( \alpha (\mu = \cos \alpha \text{ from } 0 \text{ to } 90^\circ) \), and kinetic energy \( E \) from 0.15 to 400 keV. The subscription \( l \) represents the equatorial plane, \( p \) indicates the equatorial plane, \( \gamma \) is the Lorentz factor, and \( h \), which is proportional to the bounce period along magnetic field lines, is defined by:

\[
h(\mu_o) = \frac{1}{2Re} \int_{r_o}^{r_m} \frac{ds}{\sqrt{1 - \frac{B(s)}{B_m}}} \tag{2} \]

Here, \( B_m \) is the magnetic field at the mirror point, \( ds \) is a distance interval along the field line, and \( Re \) is the distance between the Earth center and the intersection of the field line with the equatorial plane.

The time-dependent conditions that drive the variations of the above distribution function mainly lie in the following three aspects: (1) the outer boundary conditions at 6.5 \( Re \), (2) the electric field condition, and (3) the magnetic field condition.

1. The outer boundary condition, assumed isotropic, is obtained from the Los Alamos geosynchronous spacecraft that measure particle fluxes at various energy channels. The measured ion fluxes are decomposed into different ion species according to their statistical fractions derived by D. T. Young et al. (1982). These fractions vary as a function of Kp index and F10.7.

2. The convective electric field or the electric potential is self-consistently estimated within the ring current model (Yu et al., 2017). Note that while the corotation electric field is included in this study, the inductive electric field is not included. Mapped to the equatorial plane, the ionospheric electric potential \( \Phi \) is determined by field-aligned currents (FACs, \( J_b \)) and ionospheric conductance based on the following Poisson equation:

\[
\nabla \cdot (\Sigma \nabla \Phi) = -J_b \sin I \tag{3} \]

The above solver has a high-latitude boundary that corresponds to the outer boundary of the ring current model. The electric potential at this boundary is specified by the Weimer model (Weimer, 2001), which is
driven by solar wind conditions. The FACs $J_o$, mainly Region-2 type, are diverted from the partial ring current (Vasyliunas, 1970) in the equator. The ionospheric conductance $\Sigma$ is originated from two energy sources: the solar radiation and electron precipitation. The solar radiation induced conductance can be estimated based on empirical functions with solar zenith angle and F10.7 index (Moen & Brekke, 1993). The electron precipitation associated conductance is determined by Robinson formula (Robinson et al., 1987) that relates the conductance to the energy flux and averaged energy of precipitating electrons. These electrons are diffused into loss cones from the inner magnetosphere due to the resonant interactions with the whistler mode waves (Jordanova et al., 2012, 2016; Yu et al., 2016).

3. As for the magnetic field condition, the ring current model is coupled self-consistently to a 3-D force-balanced equilibrium code that computes the magnetic field from the anisotropic RAM plasma conditions (Zaharia et al., 2004, 2006).

With the supply of plasma source from the boundary, mostly on the nightside, the above electric and magnetic field drive the particles to move toward and around the Earth, violating the third adiabatic invariant if the global change of the magnetic field configuration is on the order of drift period of particles, thus leading to their energization and the increase of ring current intensity.

The loss processes that decrease the total ring current energy stem from both ions and electrons. Although electrons' contribution is minor to the ring current energy content as opposed to the one from ions, it is found to be not negligible as electrons could contribute as much as 20% in storms (Frank, 1967; Jordanova et al., 2012; Liu et al., 2005). In addition to being depleted at the dayside magnetopause boundary, the loss of electrons is partly caused by scattering into their loss cones and precipitating into the upper atmosphere. Such scattering process is mostly a result of cyclotron wave-particle interactions when the electrons gyrate at a frequency $\Omega_e$ that satisfies the resonant condition. Gyroresonant interactions with waves can lead particles to diffuse in pitch angle. The responsible waves included in this ring current model are whistler mode waves, such as chorus waves outside plasmapause and hiss waves inside plasmapause (e.g., Fu et al., 2011; Jordanova et al., 2016; Ni et al., 2016). In this study, the electrostatic electron cyclotron harmonic (ECH) wave is not included.

The pitch angle scattering process, or diffusion, can be accounted for via the diffusion equation:

$$< \frac{\partial F_i}{\partial t} > = \frac{1}{\hbar \mu_o} \left[ \hbar \mu_o \frac{\partial}{\partial \mu_o} F_i \right]$$

with the bounce-averaged pitch angle diffusion coefficients associated with wave-particle resonant interactions. The coefficients associated with chorus waves are determined from quasi-linear theory using the PADIE code (Glauert & Horne, 2005; Glauert et al., 2014; Horne et al., 2013), based on statistical observations of wave properties for regions outside the plasmapause. The coefficients associated with hiss waves are computed from a similar code by Albert (2005). The electrons diffused into their loss cones then precipitate and contribute changing the auroral conductance, as a major energy source to the ionosphere.

For ions, their loss processes in the model include charge exchange with geocoronal hydrogen, represented by $$< \frac{\partial F_i}{\partial t} > = -\sigma \sqrt{2E/m_i} < n_H > F_i$$ (where $\sigma$ is the charge exchange cross section and $< n_H >$ is the bounce-averaged geocoronal hydrogen density; see details in Jordanova et al., 1996), drift out of the dayside boundary, atmospheric collisional loss, and pitch angle diffusion into loss cone for precipitation. The new collisionless scattering mechanism implemented in the model is the FLC scattering, which is solved via the same diffusion equation in Equation 4. The diffusion coefficients $D_{\alpha \alpha}$ are computed based on the geometry of magnetic field lines that have minimum near the magnetic equator (a reasonable assumption for the inner magnetosphere; note that regions with magnetic minima at higher latitudes often appeared in the dayside magnetosphere (Shabansky, 1971) or regions with two current sheets off equator (Delcourt et al., 2006) are not applicable), previously formulated by S. L. Young et al. (2008):
In the above equation, \( \eta_1 = R_c (d^2 R_c / d\varepsilon^2) \) and \( \eta_2 = R_c^2 / B_0 (d^2 B_0 / d\varepsilon^2) \) are measures of the changing curvature radius \( R_c \) and magnetic field \( B_0 \) in the equatorial plane, respectively (\( \varepsilon \) is the distance along the field line away from the equator). \( \tau_B \) is the bounce period between two magnetic mirror points, related to the \( h \) parameter in Equation 2. \( \beta_0 \) is the equatorial pitch angle, at which the angle-dependent quantity \( \sin(\omega_0\varepsilon) \cos^{h}(\varepsilon) / (\alpha_0) \) reaches its maximum (S. L. Young et al. 2002). Parameters of \( a_1(\varepsilon), a_2(\varepsilon), c(\varepsilon), \) and \( d(\varepsilon) \) are determined in the form of \( q = \sum_{n = 0}^{N} g_n \varepsilon^{-n} \) with the coefficients \( g_n \) listed in Table 2 of S. L. Young et al. (2002).

From the above formula, it is evident that \( D_{\text{ax}} \) is controlled by the parameter \( \varepsilon \), which depends on not only the geometry of the in situ magnetic field lines but also the gyroradius or the mass of particles. The typical curvature radius of the magnetic field line near the equatorial plane in the nightside inner magnetosphere (e.g., \( L = 6 \)) during moderate storm time is about 0.1 \( R_e \), while the gyroradius of \( H^+ \) at \( E = 50 \) keV is about 0.08 \( R_e \) and that of \( O^+ \) with the same energy is 0.32 \( R_e \). Therefore, the ring current ions (\( H^+, \ He^+, \ O^+ \)) have comparable gyroradii and can experience scattering. Among the three species, the \( O^+ \) has the largest gyroradius, hence it would experience the FLC scattering most easily. On the other hand, the ring current electrons have much smaller gyroradius than the curvature radius, so the electrons are unlikely to be influenced by the FLC scattering process. In this study, we only consider the FLC effect on the ion scattering.

### 3. Simulation Results

In order to understand the role of FLC scattering mechanism in ion precipitation and the decay of ring current intensity, we perform two simulations with the FLC scattering process included and excluded.

\[
D_{\text{ax}} = D \frac{N^2 \sin^2(\omega(\varepsilon) \varepsilon_0) \cos^{2h}(\varepsilon) / (\alpha_0)}{\sin^2(\varepsilon \alpha_0) \cos^2(\varepsilon \alpha_0)}
\]

\[
D = \frac{A_{\text{max}}^2(c, \eta_1, \eta_2)}{2r_B}
\]

\[
N = |\sin(\omega(\varepsilon) \varepsilon_0) \cos^{h}(\varepsilon) / (\alpha_0)|^{-1} \mid_{\varepsilon = \varepsilon_0}
\]

\[
A_{\text{max}} = \exp(c(\varepsilon)) (\eta_1^{a_1(\varepsilon)} \eta_2^{a_2(\varepsilon)} + d(\varepsilon))
\]

Here \( \varepsilon = R_c/R_e \) is a parameter representing the degree of chaotic scattering due to FLC effects. \( R_c \) is the particle gyroradius in the equatorial plane, and \( R_e \) is the FLC radius:

\[
\frac{1}{R_e} = (\vec{b} \cdot \vec{V}) R
\]
respectively. The storm event is chosen at 17 March 2013, a coronal mass ejection (CME)-driven event with its minimum Dst approaching −132 nT. Figure 1 shows the solar wind, interplanetary, and geomagnetic conditions. The solar wind speed, solar wind density, and the Dst index increase sharply at 06:00 UT. The enhancement of AU/AL indices hereafter indicates substantial substorm injections. The Dst index thus decreases to −100 nT around 10:30 UT and further drops to around −132 nT at 20:00 UT, after which the recovery phase begins.

3.1. Morphology of Ion Precipitation Associated With FLC Scattering

Figure 2 shows the global distribution of the parameter \( \varepsilon \) and the corresponding pitch angle diffusion coefficients \( D_{\alpha \varepsilon} \) for different ion species at \( E = 50 \) keV and \( \alpha = 50^\circ \). All these plots are chosen at the time of the first Dst minimum (i.e., 10:30 UT). The \( \varepsilon \) value for all ion species is generally larger on the nightside than on the dayside, a result of that the nightside magnetic field lines are more stretched with smaller FLC radius. As the \( O^+ \) ion has the largest gyroradius among the three, its \( \varepsilon \) is the greatest. It would also experience the FLC scattering on the dayside since it meets the criterion of \( \varepsilon > 0.1 \) in a wider region than \( He^+ \) and even much wider than \( H^+ \). As expected, the pitch angle diffusion coefficient \( D_{\alpha \varepsilon} \) above the FLC scattering threshold, that is, the nonblank area in the plot (middle column), shows wider coverage over the globe, although the magnitude is not necessarily the largest. Figure 2 (right column) shows that in general, for individual ion species, the \( D_{\alpha \varepsilon} \) is larger at higher energies, and its peak value varies from low pitch angles for small energies to high pitch angles for large energies. At hundreds of keV, the peak of diffusion coefficients appears around 55°, suggesting that the FLC mechanism can effectively scatter higher-energy ions at intermediate pitch angles and scatter lower-energy ions at low pitch angles. For higher energies, the diffusion coefficient for the \( H^+ \) appears to be the largest among the three ions, whereas at lower energies, the diffusion coefficient for the \( O^+ \) is the largest. This indicates that for ions at a particular kinetic energy \( E \) and pitch angle, the scattering efficiency is larger for \( O^+ \) ions when \( E \) is small, but it is larger for \( H^+ \) ions when \( E \) is larger.

Figure 3 compares the total precipitating flux within the ion loss cone at different energies from two simulations at 10:30 UT. The results without FLC scattering loss show that precipitation mostly occurs on the dusk-to-nightside sector outside \( L \) of 3.5. Ions with lower energies are precipitated more. The \( H^+ \) ions show the largest precipitating flux among the three species and \( He^+ \) ions precipitate the least. Such precipitation is a result of magnetospheric convection; as the particles are transported earthward and the loss cone widens, particles with small pitch angles precipitate (Jordanova et al., 1996). Regardless of the ion species and the intensity of the flux, the global morphology of the precipitation is the same for these ions. That is, the precipitation occurs in the same MLT region outside the plasmapause for the same energy.

As the FLC scattering is included in the simulation, the precipitation on the nightside increases significantly. Among the three ion species, the \( H^+ \) and \( He^+ \) precipitation mostly takes place in the outer region (\( L > 5 \)) in the nightside sector, while the \( O^+ \) precipitation zone extends into the afternoon and morning sectors, in addition to the nightside region. Its radial coverage is also much larger on the nightside. Ions with higher energies tend to precipitate slightly in the inner region and move into the dayside sector. In contrary to the \( H^+ \) precipitation, the \( O^+ \) precipitation at \( E = 50 \) keV shows asymmetry in the global pattern. The precipitation is much less on the dawn-to-noon sector than the other area, possibly an indication on the drift path of source population as they move around the Earth.

From the global distribution of proton precipitation with the FLC scattering included, we can easily identify the sharp earthward boundary of the precipitation for these ions, which may be related to the isotropy boundary. It is evident that the precipitation boundary is not only energy and MLT dependent but also ion species dependent. For example, the boundary of \( E = 50 \) keV \( H^+ \) is around \( L = 5 \) at midnight and moves outward to \( L = 6 \) on the dawnside/duskside. In other words, the ionospheric latitude for the precipitation boundary is at the lowest latitudes on midnight and shifts to higher latitudes while moving to the dayside. Such boundary is further earthward at higher energies. In contrast, the precipitating boundary of \( O^+ \) is even closer to the Earth then the light ions. These tendencies were also reported in previous studies (e.g., Yue et al., 2014) that estimated the isotropy boundary based on the criterion of \( K = 8 \) (or \( \varepsilon = 0.125 \)). Thus, the FLC scattering may be associated with the formation of isotropy boundary, as will be discussed below.
3.2. Contribution of FLC Scattering to the Ring Current Decay and Ionospheric Precipitation

As shown above, the FLC scattering brings about substantial ion precipitation compared to the adiabatic loss by magnetospheric convection, meaning that the ring current loses a large amount of ion population. Figure 4 shows the simulated Dst index compared to the observed SYM-H index. The simulation uses Dessler-Parker-Sckopke (DPS) relationship (Dessler & Parker, 1959; Sckopke, 1966) to estimate the energy content of the ring current and then determine the associated Dst index. The ring current between 06:00 and 10:00 UT drops rapidly in both simulations, suggesting that the energization process dominates over the loss processes in the storm main phase. On the other hand, the ring current is remarkably weaker in the recovery phase when the FLC effect is considered and recovers slightly faster than the case without the FLC scattering. The difference between the two Dst indices is about 15 nT, a factor of 20%, implying that the FLC scattering of ions additionally removes about 20% of the ion population from the ring current.

**Figure 2.** The parameter $\varepsilon = R_g/R_e$ (left) for ions with $E = 50$ keV and pitch angle of 50°, the pitch angle diffusion coefficient $D_{\alpha\alpha}$ (middle) for field line scattering at $E = 50$ keV and pitch angle of 50° in the equatorial plane, and the pitch angle diffusion coefficient (right) as a function of energy and pitch angle at MLT = 24 and $L = 6.5$ at 10:30 UT of 17 March 2013.
Figure 3. The global distribution of ion precipitating flux in the equatorial plane at different energies ($E = 5.7, 50,$ and $164$ keV). For each ion species, the precipitation distribution is compared between two simulations: with FLC scattering included and excluded. The black dotted lines represent the plasmapause boundary.
ring current populations. It should be noted that the ring current model only simulates the ring current, while the observed SYM-H index represents the contribution from all types of current systems, including the magnetopause current and tail currents, which are absent in the model. This is probably the reason that the overall Dst index in the simulation is not as strong as in the observation.

We further compare the precipitation with in situ measurements from low-Earth orbit (LEO) NOAA/POES satellites. With several identical spacecraft flying along different meridians, global coverage of precipitation is obtained. We use flux data from the 0° telescopes onboard NOAA/POES satellites. These telescopes view outward along the local zenith with 30° wide and monitor particles in the loss cones. According to Rodger et al. (2010), the 0° telescopes detect only the bounce loss-cone particle populations for $L > 1.4$ but measure both precipitating and trapped populations at lower latitudes. Figure 5 (left) shows observed proton precipitation of $30 < E < 80$ keV at four MLT sectors. The data are binned every 0.5 hr with a radial resolution of 0.25 $R_e$. The proton precipitation on the dusk-to-night sector ($15 < MLT < 3$) is intense during the storm main phase as well as in the prolong recovery phase. In the storm main phase from 06:00 to 10:30 UT, the inner region with $3.5 < L < 5$ is gradually filled up with loss cone protons. In the recovery phase, the earthward inner boundary of precipitation slightly migrates outward with the precipitation intensity decreased. In the sector of $15 < MLT < 21$, the outer region ($L > 5$) shows nearly lack of precipitation after 18:00 UT, while the inner region still possesses strong precipitating flux. On the morning and dayside ($3 < MLT < 15$), the precipitation mostly occurs outside $L = 4.5$ and is much weaker in both the storm main phase and recovery phase. Figure 5 (right) shows the precipitating electron flux of $30–100$ keV for comparison. While the electron precipitation evolves in a similar manner and shows similar spatial distribution in this storm event, the precipitating electron flux is dominantly larger in the dawn sectors ($3 < MLT < 9$) than other sectors. This is consistent with electron drifting physics. Interestingly, it is found that in the nightside and dusk sectors ($15 < MLT < 21, 21 < MLT < 3$), the precipitating proton fluxes are comparable and even larger than that of electrons across a large spatial coverage ($3.5 < L < 6.5$), even though the electron flux is measured within a wider energy channel. This indicates that the precipitating protons of tens of keV could carry a significant, nonnegligible energy source down to the ionosphere in these locations. Such finding was
also recently found in a statistical study by Tian et al. (2020). This substantial energy deposition by precipitating protons in the above regions is partially confirmed by our simulation, as will be described below.

In the simulation shown in Figure 6, when the FLC scattering is excluded, the proton precipitation (30–80 keV) in the dusk-to-night sector (15 < MLT < 3) appears within a large region outside L = 3 in
the storm main phase and recovery phase, similar to the distribution in observations. However, the magnitude is notably smaller, suggesting that the loss of protons from magnetospheric convection at 30 < E < 80 keV in the model cannot account for the observed precipitation. When the FLC scattering loss is introduced, it is found that the proton precipitation in the outer zone (L > 5.5) is largely enhanced, which therefore agrees better with the observation qualitatively. In the midnight sector (21 < MLT < 3), the intensity appears larger than the data in the same zone. In the dusk sector (15 < MLT < 21), the outer zone precipitation is weaker and remarkably drops after 18:00 UT, which is consistent with the data. However, across all MLTs, the inner region (3.5 < L < 5) still lacks sufficient precipitation. This may be attributed to a less intense ring current, as indicated by the Dst index in Figure 4. Such a weaker ring current leads to a less stretching magnetic field configuration (see Figure S1 in the supporting information) that prevents more scattering of particles. Another possibility is that other scattering process, for example, wave-particle interactions, needs to be taken into account, to provide additional precipitation in the low-latitude regions, as suggested by Gvozdevsky et al. (1997) and Jordanova et al. (1997).

Similarly, with the FLC scattering loss included, the O\(^+\) precipitation is significantly enhanced in the outer zone (L > 4.5 on the nightside and L > 5 on the dayside), as opposed to the case without FLC scattering loss, in which only weak precipitation occurs in the dusk and night sectors and it is completely empty on the dayside. The O\(^+\) precipitation appears across a wider L region than the proton precipitation, although the precipitation intensity for 30 < E < 80 keV is not as large. It further shows larger flux on the dayside (9 < MLT < 15) that is missing in the proton precipitation. (Since no O\(^+\) precipitation is available from the POES satellite, comparisons are not made available.)

![Figure 7. Spatial distribution of precipitating energy flux in the ionosphere at 10:30 UT, contributed respectively by (a) electron precipitation, (b) proton precipitation, (c) helium ion precipitation, and (d) oxygen ion precipitation. The energy flux is obtained by integrating differential flux over 150 eV < E < 400 keV.](image-url)
3.3. Energy Source to the Ionosphere Due to Ion Precipitation

We further investigate the contribution of the ion precipitation to the ionospheric energy deposition by comparing with the electron precipitation. It is widely believed that the electron precipitation contains the dominant energy source into the upper atmosphere and the contribution of ions is usually omitted (Galand & Richmond, 2001; Hardy et al., 1989; Mitchell et al., 2013). With the FLC scattering process included, we compare the consequent contribution from all ion species. Figure 7 shows the spatial distribution of precipitating energy flux of electrons, protons, helium ions, and oxygen ions at 10:30 UT. The precipitating energy flux is computed by integrating the differential flux within the loss cone over 150 eV < E < 400 keV. The electron precipitation clearly dominates the energy budget from the post-midnight eastward to the dayside. On the nightside, large electron precipitation extends to latitudes as low as 51°, and the energy deposit almost reaches 10 ergs/cm²/s at MLT = 9 and MLat = 60°. In contrast, the ion precipitation is mostly centered around the midnight and decreases toward dayside. The proton energy flux is the largest among the three ion populations, followed by the oxygen and helium ions. It is noted that in the dusk-to-night sector (18 < MLT < 24, 0 < MLT < 3), the proton energy flux appears to be close to that of electrons at midlatitudes (i.e., 56° < MLat < 62°, or 5.5 < L < 6.5 as mapped to the equator), suggesting that the proton precipitation also carries considerable energy source down to the upper atmosphere in these regions. Such a scenario of precipitating protons carrying comparable energy source in the dusk-to-night sector is consistent with the observations shown in Figure 5, although the radial extent of these regions is not as large as in the observations.
Figure 8 shows the temporal evolution of precipitating energy flux at midnight (MLT = 24). The energy flux of each species is significantly enhanced after 06:00 UT as the storm begins and the nightside magnetic field stretches. The precipitating electron energy flux frequently shows enhancements at lower latitudes, probably due to enhanced wave-particle interactions during the substorm injections. From Figure 1, the AL index shows sharp decrease around 06:00, 09:30, 11:30, and 16:00 UT, respectively, suggesting substantial substorm injections (Kamide & McIlwain, 1974). They appear to correspond well to these enhancements in the electron precipitation from higher to lower latitudes. As the flux boundary conditions of the model is directly obtained from LANL satellite measurements, plasma injections occurred during substorms are captured by the model at the boundary. These injections thus bring more plasma to be scattered down to the atmosphere. The precipitating ion energy fluxes are mostly large at latitudes above 55° where the magnetospheric field undergoes stretching. The intensity of the energy flux due to proton precipitation is close to that of electrons throughout the storm main phase, indicating that on the nightside, ion precipitation owing to the FLC scattering also produces remarkable energy source to the ionosphere, which may further enhance the ionization in the upper atmosphere and local conductivity. In our next study, we will incorporate this additional energy source in the calculation of the ionospheric conductance. Again, the oxygen ions provide a larger coverage of precipitation source energy but at a secondary level in its intensity as compared to protons.

3.4. Relationship With the Isotropy Boundary

Finally, whether the FLC scattering is responsible for the formation of IB is examined. We follow the methods in Dubyagin et al. (2018) to identify the IB location from NOAA satellite observations of 30–80 keV proton fluxes. Two NOAA satellites (MetOP-02 and NOAA-19) travel through the auroral zone in the premidnight and postmidnight sector respectively during the storm event and thus provide a good opportunity to compare with simulation results because the FLC scattering process is predominantly effective on the nightside. As demonstrated in Figures 9a and 9b, across the boundary toward lower latitudes (or lower L shells), the precipitating (from 0° telescope) proton flux is lower than the trapped (from 90° telescope) proton flux and deviates more and more as moving toward equatorward (lower L shells). The two are however in comparable magnitude at higher latitudes (larger L shells) of the boundary (i.e., a signature of isotropic distribution).

Figure 9c shows IB locations (solid lines) obtained from the two satellites. During the entire storm event, although their orbits slightly shift in local times, the variation is small within 1–2 local hours. From the simulation results, we obtain the boundary along the satellite trajectory by selecting the position where the parameter of $\varepsilon = 0.1$ for protons of 50 keV, a criterion used in many previous studies (e.g., Ganushkina et al., 2005; Sergeev et al., 1983; Yue et al., 2014). It is found that since 06:00 UT, the boundary determined from the model results move to lower L shells, consistent with the trends in the data, although during the early storm main phase (from 06:00 to 08:30 UT), the model shows a much more earthward location than the data. During the late storm main phase and recovery phase (after 08:30 UT), the model’s boundary is around 4.5, while the observations show that IB locations generally fluctuate between $L = 3.5$ and $L = 4.5$, slightly closer to the Earth than the model results. Hence, the modeled IB is at larger L shells than observations by about 20%, indicating that the stretching of the nightside magnetic field lines and subsequent FLC scattering is roughly responsible for the formation of sharp IB boundaries. Close comparison indicates that the simulation-estimated boundary is slightly more outward than the data after 08:30 UT, while it is much closer to the Earth before 08:30 UT. This is probably because the modeled magnetic field.

![Figure 9](image-url)

**Figure 9.** (a, b) Two examples of determining the isotropic boundary from Metop02 and NOAA 19 satellites. Dashed black line represents the precipitating proton flux observed by 0° telescope, and solid black line represents the trapped proton flux observed by 90° telescope. (c) Comparisons of the isotropic boundary location between the observations (solid lines) and simulations (dashed lines).
configuration is not as stretching as in reality during the late storm main phase and recovery phase but is not so dipolar during early storm main phase (see Figure S1 and description).

4. Summary

In this study, we implement an additional collisionless loss mechanism in the RAM-SCB ring current model, FLC scattering, and investigate its effects on the ring current decay and contribution to the ionospheric energy source and auroral IB. The FLC scattering mechanism is solved via a diffusion equation with associated pitch angle diffusion coefficients. Ions with comparable gyroradius to the FLC radius undergo scattering and further precipitate down to the ionosphere when they are in the loss cones. The results are summarized as follows.

1. The FLC scattering mechanism can effectively diffuse ring current ions especially the O\(^+\) ions on the nightside where the magnetic field lines are more stretched. With the FLC scattering included, the ring current energy content decreases and recovers sooner, consistent with previous findings (e.g., M. W. Chen et al. 2019; Ebihara et al., 2011). In addition, we found that the heavy oxygen ions experience the scattering over a wider region than protons due to their larger gyroradius and hence larger chance of being scattered. The precipitation of protons takes place mainly on the nightside outside \(L = 5\), while the oxygen ions precipitate outside \(L = 4\) and even on the dayside.

2. The comparisons with NOAA/POES 30–80 keV proton precipitating flux demonstrate that the FLC scattering could account for the precipitation in the outer zone (\(L > 5\)) on the nightside. But more precipitating flux is needed in the inner zone down to \(L = 3.5\). The lack of precipitation in that region is probably due to a weaker ring current in the simulation. The magnetic field is less stretched and thus prevents more particles from being scattered and precipitating. Another possibility is that other scattering processes of ions, such as diffusion due to EMIC waves as suggested by, for example, Gvozdevsky et al. (1997), Jordanova et al. (1997), and Liang et al. (2014), are missing in this study. The latter is being investigated in an ongoing project in our research team.

3. Observations demonstrate that, compared to electrons, the precipitating protons of tens of keV can carry comparable or dominant energy source in the dusk-to-night sector for 3.5 < \(L < 6.5\), suggesting that the proton precipitation also contributes significantly to the ionospheric energy deposition in these regions and cannot be neglected. Such scenario is confirmed in our simulation, but it occurs over a smaller radial extent (5.5 < \(L < 6.5\) or 56° < MLAT < 62° when mapped to the ionosphere) in the simulation. The oxygen ion precipitation, although at a smaller intensity, occurs with a slightly larger coverage at midlatitudes. These additional energy sources into the ionosphere will be considered in our next study for a more comprehensive calculation of ionospheric conductance.

4. In order to examine whether the FLC scattering process is responsible for the formation of the isotropy boundary, or whether other mechanisms proposed in the literatures (e.g., Dubyagin et al., 2013; Liang et al., 2014; Sergeev et al., 2015) participate, we compare the IB, determined from NOAA satellites that travel across the premidnight and postmidnight sectors, with the FLC-associated boundary estimated in the simulation (i.e., \(\varepsilon = 0.1\), below which no scattering takes places and isotropic precipitation sharply drops). General agreement of the two locations is achieved, although a small discrepancy of about 20% exists. The model’s boundary where isotropic precipitation sharply drops during storm time is around \(L = 4.5\), while the observations show the IB at L shell of 3.5–4.5. We therefore conclude that the FLC scattering process could roughly explain the formation of IB to a large extent, but small disparity does exist, which is likely attributed to the small inconsistency in the stretching of the magnetic field configuration.

Data Availability Statement

The RAM-SCB model is available online (https://github.com/lanl/RAM-SCB). The simulation data are available at https://doi.org/10.5281/zenodo.3631152 (Yu et al., 2020).

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