Modeling the electromagnetic ion cyclotron wave-induced formation of detached subauroral proton arcs

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[1] Detached dayside proton arcs have been recently observed at Earth with the IMAGE FUV instrument as subauroral arcs separated from the main oval and extending over several hours of local time in the afternoon sector. We investigate the mechanisms causing the proton precipitation during two subauroral arc events that occurred on 23 January 2001 and 18 June 2001. We employ our kinetic physics-based model coupled with a dynamic plasmasphere model and calculate the growth rate of electromagnetic ion cyclotron (EMIC) waves self-consistently with the evolving ring current H+, O+, and He+ ion distributions. Modeled plasmaspheric densities agree well with in situ observations from geosynchronous LANL satellites and duskside plasmapause observations from IMAGE EUV but overestimate the drainage plume extent toward noon on 18 June. Global images of precipitating H+ ions are obtained and compared with IMAGE observations of proton arcs. We find that EMIC waves are preferentially excited, and proton precipitation maximizes, within regions of spatial overlap of energetic ring current protons and dayside plasmaspheric plumes and along steep density gradients at the plasmapause. The model matches very well the temporal and spatial evolution of FUV observations on 23 January. The predicted location of the proton precipitation on 18 June extends a few hours westward of the observations, and an offset of 2 hours in the convection electric field is needed to reproduce well the evolution of the proton arc. This study indicates that cyclotron resonant wave-particle interactions are a viable mechanism for the generation of subauroral proton arcs.


1. Introduction

[2] Recent observations from the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) satellite [Burch, 2000] provided the opportunity for detailed investigation of detached subauroral proton arcs. These phenomena are seen in global images from the Far Ultraviolet (FUV) Spectrographic Imager (SI) [Mende et al., 2000] at subauroral latitudes as distinct proton arcs separated from the main auroral oval. They usually extend over several hours of local time in the afternoon sector and last from 30 min to ~ 2-3 hours. Magnetically conjugate observations during some of the events demonstrate the presence of precipitating protons and the absence of precipitating electrons [Immel et al., 2002]. In addition, these arcs often appear after a change in the orientation of the Bz or By component of the interplanetary magnetic field (IMF) from negative to positive [Burch et al., 2002; Spasojevic et al., 2005]. In such cases the auroral oval contracts toward higher latitudes and separates by several degrees from the subauroral arc. Recent studies [Spasojevic et al., 2004, 2005] indicate simultaneous observations of plasmaspheric plumes and electromagnetic ion cyclotron (EMIC) waves during some of the events. Immel et al. [2005] reported ground-based observations of magnetic pulsations in the Pc1 and Pc5 ranges occurring conjugate to or in the vicinity of four detached arcs observed in 2000–2002. Studying 16 events that occurred during a 4 month period, Spasojevic et al. [2005] found that the dayside detached proton arcs are more likely to occur during geomagnetically disturbed periods when they are located at lower magnetic latitudes; during quiet conditions the arcs are less frequent and tend to be located at higher magnetic latitudes.

[3] Other types of localized aurora separated from the main auroral oval have been reported as well. Observations with the IMAGE FUV imagers revealed very short-lived (less than ~5 min) intense dayside subauroral proton flashes extending to magnetic latitudes (MLAT) as low as 60° and centered on the magnetic noon sector [Hubert et al., 2003]. These transient precipitation events are dominated by protons and are triggered by sudden enhancements of solar wind dynamic pressure. Very localized (less than 300 km in diameter) subauroral morning proton spots are occasionally...
observed with the IMAGE FUV instrument [Frey et al., 2004]. These spots appear in the dawn magnetic local time (MLT) sector (0300 to 1200 MLT) during the recovery phase of geomagnetic storms and last for 1 to 4 hours. They are related to plasmasphere refilling after geomagnetic storms and are interpreted as a result of pitch angle scattering of ions by either EMIC waves or electrostatic ion Bernstein waves. Finally, nightside detached auroras (NDA) during strong magnetic storms were studied by Zhang et al. [2005]. The NDA were observed when \( Dst \) was less than \(-130\) nT at magnetic latitudes between 45° and 55° and between 1930 and 0300 MLT. It was found that the thin arc-shaped NDA were very likely due to soft (<1 keV) ion precipitation, while thick patch-shaped NDA were caused by energetic (~10 keV) ion precipitation.

Several mechanisms were suggested for the formation of the detached proton arcs in the afternoon/dusk sector. The equatorial mapping of the detached arc to the plasmaspheric drainage plume is suggestive of a mechanism involving the interaction of hot ring current ions with cold plasmaspheric material. This is an environment suitable for the amplification of EMIC waves as first predicted by Cornwall et al. [1970] and subsequently investigated by many others [e.g., Anderson et al., 1992; Gary et al., 1995]. Scattering by EMIC waves will lead to the precipitation of ring current protons and the excitation of subauroral arcs [Burch et al., 2002; Spasojevic et al., 2004]. Another plausible mechanism is bounce-resonance of ring current protons with azimuthal Pc5 wave structures, as suggested by Immel et al. [2005]. The present paper examines the first mechanism using a kinetic ring current model that calculates self-consistently the excitation of EMIC waves from the anisotropic ring current ion populations. Two proton arc events are selected for detailed numerical simulation and analysis: the 23 January 2001 event and the 18 June 2001 event. Descriptions of the observations and the model are given in sections 2 and 3, respectively. The temporal and spatial evolutions of the resulting global images of proton precipitation are compared for the first time with equatorial projections of IMAGE observations in section 4. The main conclusions are summarized in section 5.

### 2. Observations

Global observations from the IMAGE FUV instrument indicated signatures of subauroral precipitation in the afternoon sector beginning around 2100 UT on 23 January 2001 [Immel et al., 2002; Burch et al., 2002]. The proton aurora brightened significantly around 2300 UT and separated from the main oval arc, which receded by several degrees toward the pole. The detached proton arc was observed until ~0025 UT on 24 January, after which the
spacecraft could no longer image the northern auroral oval. Figure 1 (top) shows an FUV image acquired on 23 January 2001 at 2323 UT. The strongest subauroral emissions (shown with an arrow in Figure 1, left) were observed in the 1500–1700 MLT sector at ~65° magnetic latitude (MLAT). The image is mapped to the Geocentric Solar Magnetospheric (GSM) equatorial plane using the Tsyganenko and Stern [1996] magnetic field model (Figure 1, right). In the equatorial plane, the detached arc extended between $L \sim 5$ and $L \sim 8$ in the afternoon sector. Electron and ion spectra from the FAST electrostatic analyzers were obtained in the same local time sector, conjugate to the IMAGE observations [Immel et al., 2002]. The FAST ion spectrometer measured proton fluxes at energies less than 30 keV and showed significant proton precipitation equatorward of ~69° MLAT at the time of the detached arc observation by IMAGE. There was no enhancement in the electron precipitation at these latitudes. Modeling the response of the IMAGE WIC camera, Immel et al. [2002] showed that precipitation of ~20 keV protons would be consistent with these emissions.

[6] The second detached proton arc event we investigate occurred on 18 June 2001. Bright proton aurora was observed from ~1440 to 1500 UT between ~64° and 70° magnetic latitude [Spasojevic et al., 2004]. At ~1455 UT the main auroral oval contracted poleward and an equatorward proton arc detached from it and became separated by several degrees. The detached arc was observed until ~1620 UT, after which the emissions began to fade. An FUV image acquired on 18 June 2001 at 1530 UT and mapped to the GSM equatorial plane using the Tsyganenko and Stern [1996] magnetic field model is shown in Figure 1 (bottom). The detached proton arc is shown with an arrow in Figure 1 (left). When mapped to the equatorial plane (Figure 1, right), the emissions extended in the afternoon sector from $L \sim 5$ to $L \sim 8$ and between ~1300 and ~1630 MLT. The NOAA-16 satellite, which has an orbit at ~830 km in the ~1300–0100 MLT meridian plane, overflew this proton arc at ~1540 UT. Particle data from the MEPED instrument on board this satellite indicated a local increase in the precipitating 30–80 keV ion flux at ~1300 MLT and $L \sim 7.5$, equatorward of the main auroral oval (not shown).

[7] Solar wind data from the Advanced Composition Explorer (ACE) are shown in Figure 2. The proton arc events occurred during the time intervals identified with vertical dashed lines. An interplanetary shock was observed on 23 January (Figure 2, left) at hour ~34. Behind the shock, the density increased to ~15 cm$^{-3}$ and the solar wind speed reached values of ~475 km/s. There was a southward to northward turning of the IMF between hours ~42 and ~46, followed by a westward to eastward turning between hours ~46 and ~47 [Burch et al., 2002]. During this event the geomagnetic activity was moderate, with indices $Kp = 4$ and $Dst = -25$ nT. The second proton arc event occurred on 18 June 2001 (Figure 2, right) during the recovery phase of a moderate geomagnetic storm with minimum $Dst = -61$ nT and maximum $Kp = 5^+$. During IMAGE observations (between hours ~38 and ~41) the solar wind density was ~45 cm$^{-3}$, the solar wind velocity was ~360 km/s, and the geomagnetic indices were $Kp = 4^+$ and $Dst \sim -40$ nT.

[8] During 22–24 January and 17–19 June several Los Alamos National Laboratory (LANL) satellites provided ion flux measurements at geosynchronous altitudes. Spectra from the Magnetospheric Plasma Analyzer (MPA) [McComas et al., 1993] on these satellites, which measures the distributions of ions and electrons in the energy range ~1 eV to 40 keV, are shown in Figure 3 (left) for 23 January and in Figure 3 (right) for 18 June. The nightside geosynchronous observations provide information on the ring current source populations; the hot ion fluxes (energy >1 keV) measured by the MPA on satellite 1994–084 (third panel from top) have larger values between 1800 and 0600 MLT on 18 June (Figure 3, right) reflecting the more elevated magnetic activity than on 23 January (Figure 3, left). Geosynchronous measurements also contain information about the strength of the electric field, as discussed in detail by Thomsen et al. [2002]. The enhanced electron fluxes above ~100 eV correspond to fresh plasma sheet plasma, i.e., newly arrived particles on open drift trajectories from the more distant tail. In particular, the energy of the upper cutoff in the plasma sheet electron spectrum (see arrow in Figure 3, left) is a measure of the depth of penetration of the plasma sheet into the near-Earth region. It typically increases with increasing local time. Following the procedure described by Thomsen et al. [2002], we use that cutoff energy to help determine the strength of the convection applied in the simulations. The procedure is described in greater detail in section 3.

[9] MPA measurements of cold ion density (in the energy range ~1 eV to 100 eV) give additional information on the geomagnetic conditions. On 23 January (Figure 3, left) a plasmaspheric plume (cold plasma density >10 cm$^{-3}$) was observed by the LANL 1989–046 MPA (top panel) from ~0500 UT until ~0700 UT (1800–2000 MLT) and by the LANL-01A MPA (fifth panel) from ~1100 UT until ~1630 UT (1200–1730 MLT). On 18 June (Figure 3, right) a plasmaspheric plume was crossed in the dayside sector by LANL 1994-084 (third panel) from ~0430 UT until ~0930 UT (1100–1600 MLT) and by LANL-01A (fifth panel) from ~1000 UT until ~1700 UT (1100–1800 MLT). Global observations of the plasmasphere were provided concurrently by the Extreme Ultraviolet (EUV) imager [Sandel et al., 2001] on board the IMAGE satellite. This instrument has a lower sensitivity threshold equivalent to total ion density of ~40 cm$^{-3}$ [Goldstein et al., 2005]. Unfortunately, no IMAGE EUV plasmaspheric data were available during the January proton arc event. On 18 June 2001 the global images indicated the formation of a dayside plume of sunward flowing plasma [Spasojevic et al., 2004] from ~0500 to 1600 UT in agreement with LANL observations of a dayside drainage plume. Detailed comparisons of these data with simulation results from our model are discussed in next section.

3. Global Kinetic Model

[10] We investigated ring current dynamics during the January and June 2001 proton arc events using our global ring current-atmosphere interactions model (RAM) briefly summarized below (for further details, see Jordanova et al. [1996, 1999, 2003]). The model solves numerically the bounce-averaged kinetic equation for the distribution func-
Figure 2. (left) Interplanetary observations from the MFI and SWEPAM instruments on ACE during 22–24 January 2001. From top to bottom are shown proton density, solar wind bulk speed, solar wind dynamic pressure, magnetic field strength, the $B_z$ (GSM) component of the magnetic field, the measured $Dst$ index, the planetary $Kp$ index (solid) and the effective $Kp$ index (dashed-dotted line, see definition in section 3). (right) Interplanetary observations during 17–19 June 2001. The vertical dashed lines bracket the time period of proton arc observation.
Figure 3. (left) Energy spectrograms of the magnetospheric plasma analyzer (MPA) ion and electron plasma data from three geosynchronous LANL satellites (indicated on the vertical axis) on 23 January 2001. The ion (electron) energy flux is plotted as a function of the logarithm of the ion (electron) energy $E_i$ ($E_e$) and time. Open (solid) triangles on the UT axis indicate local noon (midnight). The arrow on the bottom panel indicates the observed upper cutoff in the plasma sheet electron spectrum, which can be related to the strength of the electric field [c.f. Thomsen et al., 2002]. The intense (yellow to red) ion fluxes below $\sim 10$ eV indicate the traversal of a plasmaspheric plume. (right) MPA energy spectrograms on 18 June 2001.
tions of H⁺, O⁺, and He⁺ ions in the equatorial plane for radial distances from 2 to 6.5 Re and all MLT, kinetic energy from ~100 eV to 400 keV and equatorial pitch angle from 0° to 90°. In the present study the time-dependent earthward transport and acceleration were calculated using a high time resolution convection electric field model and a dipole model of the Earth’s magnetic field.

[11] The strength of the cross-tail electric field is known to be well correlated with the 3-hour index Kp [e.g., Thomsen, 2004, and references therein]. At higher time resolution, the equatorward boundary of the auroral electron precipitation observed by the DMSP satellite and reported as the Auroral Boundary Index (ABI) [Gussenhoven et al., 1981, 1983] provides a similarly good monitor of the strength of the convection [Thomsen, 2004]. For the simulations described here, we use the tabulated value of ABI to control the strength of the convection by first converting it to an effective Kp through the relationship derived by Gussenhoven et al., namely \( K_{p,eff} = (67.8 - \text{ABI})/2.07 \). This effective Kp then determines the strength of the electric field through the relationship derived by Maynard and Chen [1975] for a Volland-Stern type electric field with a shielding parameter of 2 [Volland, 1973; Stern, 1977] in a dipole magnetic field. The procedure is described in greater detail by Korth et al. [1999]. Finally, in order to model the sudden electric field enhancements that deliver plasma sheet material deep into the inner magnetosphere, we use the upper cutoff of the plasma sheet electron spectrum observed by the geosynchronous satellites and the known local time of the measurement to solve for a matching value of Kp, following Thomsen et al. [2002]; we override the ABI-determined electric field when such enhancements occur. The resultant effective Kp is shown in the bottom of Figure 2, where it is compared to the corresponding true 3-hour Kp index. This effective Kp index exhibits general trends similar to the planetary Kp index, but it has much finer time resolution and was used to drive our cross-tail potential model.

[12] To simulate the time-variant plasma inflow at the nightside boundary of the model we used ion flux measurements from the MPA (Figure 3) and the Synchronous Orbit Particle Analyzer (SOPA) [Belian et al., 1992] (energy >50 keV) on LANL satellites; these satellites provided very good coverage of the time-varying conditions at geosynchronous orbit in response to solar wind changes. All major ion loss processes were included in our model simulations: charge exchange with hydrogen geocorona, Coulomb collisions with plasmaspheric electrons and ions, scattering by EMIC waves, and losses at low altitudes and through the dayside boundary.

[13] The plasmaspheric electron density in the equatorial plane was calculated using the time-dependent model of Rasmussen et al. [1993], which is coupled with our ring current model and employs the same electric and magnetic fields. This plasmasphere model calculates changes in the total flux tube content by following the motion of individual flux tubes due to the \( \mathbf{E} \times \mathbf{B} \) drift, and taking into account the ionospheric supply and loss, using the MSIS model [Hedin, 1987] of the neutral atmosphere and the ionospheric IRI model [Bilitza, 1986]. Plasmaspheric densities obtained from the Rasmussen et al. model are used to calculate the ring current losses due to Coulomb collisions, as well as in the EMIC wave growth rate calculations. Figures 4 (left) and 5 (left) show the evolution of the plasmaspheric electron density during 22–24 January and 17–19 June, respectively. The diamond symbols indicate the model plasmapause, i.e., the location of a steep gradient in electron density, identified in the model as the region where the density drops by a factor of 5 or more over a radial distance of 0.25 Re. During periods of increased convection (larger Kp index) the plasmasphere was eroded on the nightside, and at larger L shells enhanced densities were confined to the postnoon plasmaspheric plumes. As the activity level decreased, the plasmasphere corotated and expanded, refilling from the ionosphere. The solid line in Figure 5 (left) shows the plasmapause identified from IMAGE EUV data as a density drop below the sensitivity threshold of the instrument. The model reproduced well the duskside plasmapause location determined from EUV data on 18 June. However, the model predicted larger densities near 1300–1500 MLT than observed by the EUV imager at hour ~40 (Figure 5e).

[14] Comparisons of calculated densities at \( L = 6.5 \) with cold ion density measurements along the trajectories of LANL spacecraft are shown in Figures 4 (right) and 5 (right) in an MLT-UT format. The dark symbols on each trajectory indicate where plasmaspheric plumes (densities larger than 10 cm⁻³) were observed, whereas the open triangles and squares bracket densities larger than 10 cm⁻³ calculated with our model. In general, the model values were in good agreement with the in situ observations of plasmaspheric plumes at geosynchronous orbit throughout the intervals. The proton arc (red diamond line) observed on 23 January extended from ~1300 to ~1800 MLT, while the plasmaspheric plume predicted by our model extended from 1300 to 1600 MLT. The proton arc observed on 18 June occurred ~1 hour later in local time (between ~1430 and 1800 MLT) than the model prediction of the plasmaspheric plume (between ~1330 and 1600 MLT).

[15] We calculated self-consistently the growth rate of EMIC waves by solving the linearized dispersion relation with ring current parameters and plasmaspheric densities obtained simultaneously from RAM. The convective growth rates were then integrated along field-aligned wave paths to obtain the wave gain, and the wave amplitudes were calculated using a semiempirical model [Jordanova et al., 2003] since the background noise level from which the waves grow is not well known. The wave path at the plasmapause was assumed to be twice as long (±10°) due to the guiding of the waves along steep density gradients. The scattering of ring current ions by plasma waves is implemented in RAM using quasi-linear theory as a diffusive process. A unique feature of our model is the use of multi-ion diffusion coefficients [Jordanova et al., 1996] which take into account the heavy ion plasma components and thus reduce significantly the lifetimes of ~10–100 keV ions compared to diffusion lifetimes in pure electron-proton plasma. Only pitch angle diffusion was considered in this study since pitch angle diffusion rates are usually faster than energy diffusion rates.

[16] The wave gain calculations for the He⁺ band (between the O⁺ and He⁺ gyrofrequencies) EMIC waves are shown in Figure 6 for the 23 January and the 18 June proton arcs. Wave-particle interactions are negligible if the integrated
Figure 4. (left) The 3-hour index Kp (solid) and the effective Kp (dashed-dotted line). (a through f) Equatorial plasmaspheric electron densities (cm$^{-3}$) at selected hours after 0000 UT on 22 January 2001 indicated with stars on the Kp plot. The diamonds indicate the plasmapause as determined from our model simulations. (right) Local times when cold ion densities larger (smaller) than 10 cm$^{-3}$ are observed by the geosynchronous LANL spacecraft indicated with stars (dots). For given universal time, model densities bigger than 10 cm$^{-3}$ are calculated at $L = 6.5$ at local times between MLT minimum (squares) and MLT maximum (triangles). The red diamond line shows the MLT when the proton arc was observed.
Figure 5. Model simulations and data during 17–19 June 2001 in the same format as Figure 4. (a through f) The plasmapause location determined from IMAGE EUV data is plotted with a solid line.
wave gain is below 20 dB (the wave amplitudes are below 0.1 nT). Geoeffective plasma waves are thus preferentially excited along the plasmapause or at larger L shells in regions of enhanced plasmaspheric densities occurring within dayside drainage plumes. The wave excitation increased after fresh ion injections from the magnetotail and westward ion drift through the duskside magnetosphere. On 23 January (Figure 6, left) the wave gain reached a maximum in the postnoon MLT sector at \( L > 6 \) between hours 47 and 48, and vanished by hour 49 due to the wave scattering feedback and isotropization of the proton ring current. On 18 June (Figure 6, right) the wave instability maximized between hours 37 and 40 at \( L \approx 5.5 \) and extended from \( \sim 1300 \) to 1700 MLT. Similar results were obtained by Spasojevic et al. [2004], who calculated the maximum EMIC wave growth rate at geosynchronous orbit and found that the waves were unstable throughout the disturbance period on 18 June from 1200 UT to 1400 UT and later around 1600 UT in the postnoon region of enhanced plasmaspheric density.

4. Modeled Proton Precipitation

[17] Global images of precipitating proton fluxes calculated with our model during the 23–24 January 2001 and the 18 June 2001 events are displayed in Figures 7 and 8, respectively. These total precipitating fluxes were obtained by averaging the directional fluxes over pitch angles in the equatorial loss cone (corresponding to particles mirroring below 200 km altitude) and integrating over three (low, medium, and high) energy ranges. The subauroral precipitation region observed with IMAGE FUV was mapped to the equatorial plane and plotted with a diamond line in Figures 7 and 8. When there was not a distinct subauroral arc, at hour 47 (Figures 7a and 7e) and hour 49 (Figures 8a and 8e) the line shows the equatorward edge of the auroral oval. To isolate the effects of wave-particle interactions, we show fluxes calculated without (Figure 7, left) and with (Figure 7, right) EMIC wave scattering included. It is evident that wave-particle interactions enhanced significantly the ion precipitation within localized regions in the afternoon sector where EMIC wave instability developed (compare Figures 7b and 7c with Figures 7f and 7g, respectively).

[18] On 23 January 2001 our model predicted weak proton precipitation from EMIC wave scattering beginning around hour 47; its position matched the observed equatorward edge of the auroral oval (Figure 7e). By hour 47.5 the observed proton arc was well developed, and its projection onto the equatorial plane bounded the region of strong proton precipitation from EMIC wave scattering predicted with our model (Figure 7f). Note that in agreement with FAST data [Immel et al., 2002] the 10–40 keV precipitating fluxes were the strongest in the model, indicating that the proton arc emission was caused mainly by precipitating ions in this energy range. After hour 48 the observed proton arc receded to higher magnetic latitudes and the emission started to fade. There was no significant precipitation predicted by our model at hour 49, in very good agreement with these observations.

[19] The precipitating \( H^+ \) fluxes calculated with our model including drift, collisional losses, and EMIC wave-induced scattering are compared with IMAGE FUV observations on 18 June 2001 in Figure 8 (left). The modeled
Figure 7. Precipitating proton number flux (1 cm$^{-2}$ s$^{-1}$) for three energy ranges, 1–10 keV, 10–40 keV, and 40–200 keV at selected hours after 0000 UT on 22 January 2001 as a function of radial distance in the equatorial plane and magnetic local time, (a through d) considering only drift and collisional losses and (e through h) considering drift, collisional losses, and scattering by EMIC waves. The diamond line indicates the low-latitude boundary of FUV images of proton precipitation mapped to the SM equatorial plane using Tsyganenko and Stern [1996] magnetic field model.
Figure 8. Precipitating proton number flux ($1 \text{ cm}^{-2} \text{s}^{-1}$) for three energy ranges, 1–10 keV, 10–40 keV, and 40–200 keV at selected hours after 0000 UT on 17 June 2001 as a function of radial distance in the equatorial plane and magnetic local time using a convection electric field (a through d) without offset and (e through h) with a 2-hour eastward offset. The diamond line indicates the low-latitude boundary of FUV images of proton precipitation mapped to the SM equatorial plane using Tsyganenko and Stern [1996] magnetic field model.
5. Summary and Conclusions

We investigated ion cyclotron wave-particle interactions as the causative mechanism for the ion precipitation observed during two subauroral proton arc events by the FUV imager on the IMAGE satellite. Both events were seen in the postnoon local time sector, the first one occurring on 23 January 2001 and the second one on 18 June 2001. On 23 January there were observations of <30 keV proton precipitation conjugate to the proton arc by the FAST spectrometer [Immel et al., 2002]. A plasmaspheric plume overlapping the proton arc position mapped to the equatorial plane was observed by IMAGE EUV on 18 June. The MPA analyzers on LANL spacecraft measured plasmaspheric ion densities >10 cm\(^{-3}\) at geosynchronous orbit during both events concurrent with the proton arc observations.

We simulated ring current \(\mathrm{H}^+\), \(\mathrm{O}^+\), and \(\mathrm{He}^+\) ion dynamics during these two events with our global kinetic model coupled with a time-dependent plasmasphere model. We used a high time resolution convection electric field model driven by an effective \(Kp\) index, inferred either from the equatorward boundary of the auroral electron precipitation or from the upper cutoff of the plasma sheet electron spectrum. We calculated self-consistently the growth rate of EMIC waves excited by the anisotropic ion distributions as time progressed. Ring current ions were scattered into the loss cone due to resonant interactions with EMIC waves and precipitated into the atmosphere. We showed for the first time comparisons of the resulting proton precipitation with IMAG E FUV observations of detached proton arcs mapped to the equatorial plane.

We found that our model reproduced very well both the spatial and temporal evolution of the subauroral proton arc on 23 January. Strong EMIC wave growth was predicted between 2300 UT and 2400 UT within the high-density plasmaspheric plume and along the plasmapause, causing intense proton precipitation in the afternoon sector in agreement with FUV proton arc observations. However, the proton precipitation predicted with our model on 18 June extended spatially more toward noon than the observed proton arc. Using a convection electric field with a 2-hour eastward offset, the modeled precipitation matched not only the temporal but also the spatial evolution of the observed subauroral emission.

We calculated the total precipitating flux for three energy ranges: 1–10 keV, 10–40 keV, and 40–200 keV. The 10–40 keV fluxes were the strongest during both events, indicating that precipitating ions in this energy range are the primary cause of the proton arc emissions. In agreement with observations, the ion precipitation lasted for several hours and then disappeared as the ring current distributions became isotropic and stable to EMIC wave excitation.

This study demonstrated that scattering by EMIC waves is a plausible mechanism for the ion precipitation during detached subauroral proton arcs. We also showed that ring current evolution and ion precipitation patterns depend significantly on the dynamics of the convection electric field. More simulation studies of proton arcs are planned to further confirm these results. Specifically, the modeling region will be extended to larger \(L\) to include a bigger portion of the proton arc emission. We will also include self-consistent calculations of the inner magnetosphere electric and magnetic fields.

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References

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