Effects of EMIC Wave Scattering on Energetic Ions and Electrons

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• The kinetic approach for studying inner magnetospheric dynamics
• Simulations of ring current $H^+$, $O^+$, and $He^+$ ion and $e^-$ dynamics and EMIC wave excitation during geomagnetic storms
• Effect of EMIC wave scattering on:
  - ring current evolution
  - subauroral proton arcs
  - radiation belt dynamics

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Ring Current – Plasmasphere Coupling

- Ring Current Ion (1-300 keV) Density Isocontours
- Conjugate SAR Arcs
- Anisotropic Energetic Ion Precipitation
- Coulomb Collisions Between Ring Currents and Thermals (Shaded Area)
- Ion Cyclotron Wave Scattering
- Isotropic Energetic Ion Precipitation
- Cold (~1 eV) Plasmaspheric Plasma
- Plasmapause
- (L~4)
- (L~6)
IMAGE/FUV data on 23 January 2001 mapped to the magnetic equator. The proton arc was observed until ~24 UT after which the spacecraft began its perigee pass.

Energy spectrograms of precipitating electrons and ions measured by the FAST electrostatic analyzer (energies $<30$ keV) conjugate to the IMAGE observations.

Three peaks in the ion energy flux, no peaks in the electron energy flux equatorward of $\lambda=-69.5^\circ$.

Consistent with DMSP observations of 3-30 keV proton precipitation above the detached arc and <10 keV protons over the main oval.

What causes this proton precipitation? [Immel et al., 2002]
Fig. 3. Convective growth rate versus normalized frequency resulting from the same series of energetic components described in Figure 1. The cold plasma has the same density as in Figure 1 but now contains a mixture of ions (65% H+, 30% He+, 5% O+).

[Kozyra et al., 1984]

Fig. 8. Same as for Figure 3 but for a cold background plasma (65% H+, 30% He+, 5% O+) with density of 500 cm⁻³.
Kinetic Equation for Relativistic Particles

\[
\frac{\partial F_t}{\partial t} + \frac{1}{R_o^2} \frac{\partial}{\partial R_o} \left( R_o^2 \left\langle \frac{dR_o}{dt} \right\rangle F_t \right) + \frac{\partial}{\partial \varphi} \left( \left\langle \frac{d\varphi}{dt} \right\rangle F_t \right) + \frac{1}{\gamma p} \frac{\partial}{\partial E} \left( \gamma p \left\langle \frac{dE}{dt} \right\rangle F_t \right) + \frac{1}{\hbar (\mu_o) \mu_o} \frac{\partial}{\partial \mu_o} \left( h (\mu_o) \mu_o \left\langle \frac{d\mu_o}{dt} \right\rangle F_t \right) =
\]

\[
\left\langle \left( \frac{\partial F_t}{\partial t} \right)_{rd} \right\rangle + \left\langle \left( \frac{\partial F_t}{\partial t} \right)_{\text{charge exchange}} \right\rangle + \left\langle \left( \frac{\partial F_t}{\partial t} \right)_{\text{Coul collis}} \right\rangle + \left\langle \left( \frac{\partial F_t}{\partial t} \right)_{\text{wpi}} \right\rangle + \left\langle \left( \frac{\partial F_t}{\partial t} \right)_{\text{atm}} \right\rangle
\]

where

\[
\left\langle \left( \frac{\partial F_t}{\partial t} \right)_{rd} \right\rangle = R_o^2 \frac{\partial}{\partial R_o} \left( \frac{1}{R_o^2} \left\langle D_{R_o R_o} \right\rangle \frac{\partial F_t}{\partial R_o} \right)
\]

and \( \gamma = 1 + \frac{E}{m_o c^2} \)

\( R_o \) - radial distance in the equatorial plane

\( \varphi \) - azimuthal angle

\( p \) - relativistic momentum

\( \mu_o = \cos(\alpha_o) \), where \( \alpha_o \) is equatorial pitch angle

\( \gamma \) - relativistic factor, \( m_o \) - rest mass,

\( D_{R_o R_o} \) - radial diffusion coefficients

\[
\langle \chi \rangle = \frac{1}{S_B} \int_{s_m}^{s_m'} \frac{ds}{\sqrt{1 - B(s)/B_m}}
\]
Kinetic Model of Ring Current - Atmosphere Interactions

RAM --- Jordanova et al. [2001; 2006], Jordanova and Miyoshi [2005]
Calculates the distribution function of H⁺, O⁺, and He⁺ ions and e- and thermal plasma from the fundamental kinetic equations

Ring current & radiation belt model

- E~1 keV – few MeV
- PA= 0° – 90°
- dipole (L= 2.0-6.5)
- all MLT

sources

- plasma sheet - LANL
- initial distribution - Polar

losses

- charge exchange
- Coulomb collisions
- atmospheric loss
- w-p interactions
- escape from MP

transport

- convection & radial diffusion
- ionosphere/thermosphere

Plasmasphere model
Solve the hot plasma dispersion relation for \textbf{EMIC} waves:

\[
\frac{\gamma}{\sqrt{g}} = \Psi \left( n_t, E_{\|}, A_t \right)
\]

where \( n_t, E_{\|}, A_t \) are calculated with our kinetic model for \( \text{H}^+, \text{He}^+, \) and \( \text{O}^+ \) ions.

Integrate the local growth rate along wave paths and obtain the \textbf{wave gain} \( G \) (dB).

Use a semi-empirical model to calculate the wave amplitude \( B_w \) from the wave gain \( G \):

\[
B_w = \begin{cases} 
B_{sat} &= 10 \text{ nT} \quad \text{for} \quad G > G_{\text{max}} \\
&= B_{sat} \times 10^{(G-G_{\text{max}})/G_{\text{min}}} \quad \text{for} \quad G_{\text{min}} < G \leq G_{\text{max}} \\
&< 0.1 \text{ nT (neglect)} \quad \text{for} \quad G < G_{\text{min}}
\end{cases}
\]
Main phase of a large geomagnetic storm:

L=5.5
MLT=16

Energies:
- 68 keV
- 20 keV
- 8 keV
- 3 keV

\[ B_w = 0.5 \text{ nT} \]
\[ \tau = 12.5 \text{ hrs} \]

\[ B_w = 9.4 \text{ nT} \]
\[ \tau = 10 \text{ min} \]
Lifetime of ring current protons determined by:

- charge exchange losses
- WPI in electron-proton plasma
- WPI in plasma consisting of 77% H⁺, 20% He⁺, and 3% O⁺

L=4 & \( N_e = 500 \text{ cm}^{-3} \)

[Jordanova et al., 1996]
An interplanetary shock was observed at ~16 UT, October 21.

IMF $B_z \sim -20$ nT & solar wind speed $v \sim 700$ km/s; a 2nd negative $B_z \sim -15$ nT excursion at hour~33.

Triggered a large geomagnetic storm with $D_{st} \sim -170$ nT; strong geomagnetic activity lasting for about a day.

Two enhancements of $K_p = 8^-$ and $K_p = 7^+$ occurred at hour~22 and hour~40.
EMIC Wave Excitation and Ion Precipitation: October 2001 Storm

- We calculated the wave growth of EMIC waves from the He\(^+\) band (between O\(^+\) and He\(^+\) gyrofrequency)
- Intense EMIC waves are generated near Dst minima and during the recovery phase
- Ion precipitation is significantly enhanced within regions of EMIC wave instability co-located with enhanced cold plasma density
Proton precipitation losses become of the order of charge exchange losses near minimum $Dst$ when radial diffusion and WPI are considered.
Direct link between a subauroral arc and a global observations of a plasmaspheric plume by IMAGE [Spasojevic et al., 2004]

EMIC waves are excited in the afternoon MLT sector causing intense ion precipitation [Jordanova et al., 2007]
**Input Parameters in RAM-electron**

**source**
- plasma sheet
  - LANL SOPA & MPA
- initial distribution
  - AE8 and Polar/HYDRA
- w-p interactions

**loss**
- inside PP: PA diffusion from *hiss* and *lightning whistlers* (wave-source: *Abel and Thorne* [1998], *Albert* [1999])
- outside PP: life time due to strong diffusion and chorus (empirical scattering rate: *Chen and Schulz*, [2001])

**transport**
- Coulomb collisions
  - PA diffusion and energy decrease
- convection
  - *Volland-Stern + Maynard-Chen* (Kp)
- radial diffusion
  - *Brautigam and Albert* [2000] (Kp)
\[ \frac{\omega - k \cdot v_{||}}{\gamma} = n\Omega \]

Wave-Particle Interactions Within Plasmasphere

+ quasi-linear approach \hspace{1cm} (Lyons, Thorne, and Kennel [1972])
relativistic Landau and cyclotron resonance \((n=\pm 5)\)

+ wave sources

\begin{itemize}
  \item plasmaspheric hiss
  \item lightning whistler
  \item VLF transmitters (2 sources)
\end{itemize}

assumed wave normal is 45 (deg)

* The life time due to wave-particle interaction is evaluated from quasi-linear approach. In this model, three different wave sources within plasmasphere are assumed.

cf. Abel and Thorne [1998], Albert [1999]
• During quiet period, the electron loss is larger than radial diffusion, so the peak of the outer belt would move outward.
• During active period, the radial diffusion increases and plasmapause shrinks, so the peak of the outer belt would move toward the earth.
**RAM Electron Results**

- Enhancement near **dawn** for lower energies electrons
- Good agreement with NOAA electron data

[Miyoshi et al., JGR, 2006]
Energy gain from convective transport is much larger than that from diffusive transport.

The hot electron which is subject to convective transport contributes mainly to total energy gain.

Energy gain from adiabatic transport concentrates on Dst minima, and energy gain in the recovery phase can be negligible.
**Electron scattering**

EMIC (L-mode) can resonate with energetic electrons and the possibility that EMIC contribute electron loss is suggested. (e.g., Summers and Thorne, 2003, Albert, 2003)

![Graph showing electron scattering]

X-ray observations showed strong precipitation of MeV electrons, suggesting selective pitch angle scattering by EMIC waves which are often generated at dusk side. (Lorentzen et al., 2000)
Electro-magnetic ion cyclotron (EMIC) waves

Governing equation of the pitch angle scattering with quasi-linear approach

\[
\left\langle \left( \frac{\partial Q_t}{\partial t} \right)_{wpi} \right\rangle = \frac{1}{h(\mu_o)\mu_o} \frac{\partial}{\partial \mu_o} \left[ \left\langle D_{\mu_o\mu_o} \right\rangle h(\mu_o)\mu_o \frac{\partial Q_t}{\partial \mu_o} \right]
\]

\[
\left\langle D_{\mu_o\mu_o} \right\rangle \text{ is bounce-averaged diffusion coefficient (Albert, 1999, 2003)}
\]

<included wave sources>

- EMIC -- He+ band is evaluated from RAM-ions.

chorus

strong diffusion for lower energy electrons & empirical life time of pitch angle scattering are used.

\[
\tau_{wp}(Kp) = \tau_0(E, L) \times (1.0 - 0.15Kp)
\]
Main phase of a large magnetic storm:

L=5
MLT=13

Energies:
- 1500 keV
- 720 keV
- 350 keV
- 100 keV

B_w=10 nT
τ_min=few sec for 1 MeV

L=5
MLT=14

B_w=0.3 nT
τ_min=3 hours for 1 MeV
=> The electron pitch angle distributions become isotropic due to strong scattering by EMIC waves.
RAM Results: Radiation Belt Electron Fluxes

MLT=14, PA=75, UT=2, Oct 22

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<th>L</th>
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MLT=14, PA=75, UT=2, Oct 22

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</table>
RAM Results: Radiation Belt Electron Precipitating Fluxes

- Precipitating (1-4 MeV) electron fluxes without or with EMIC wave scattering
- **Pitch angle** scattering has large effect within areas of EMIC wave instability during storm recovery phase
- **Non-local** effects of WPI due to transport and diffusion
During storm-time EMIC waves are excited by the anisotropic ring current ion populations (mainly $\text{H}^+$), however, their generation and propagation characteristics depend strongly on the presence of both cold and energetic heavy ions (mainly $\text{He}^+$ and $\text{O}^+$) in the plasmas.

The growth of EMIC waves is enhanced after the fresh ion injection from the magnetotail and westward ion drift through the duskside magnetosphere. It reaches maximum in the postnoon MLT sector within regions of enhanced cold plasma density (plasmaspheric plumes) and along the plasmapause.

Wave-particle interactions enhance significantly the ion precipitation. The temporal and spatial evolution of precipitating $\text{H}^+$ fluxes is in good agreement with IMAGE FUV observations.

Ring current precipitation losses become of the order of charge exchange losses when strong waves are excited near $\text{Dst}$ minimum.

A simulation with RAM of radiation belt electron dynamics showed that EMIC waves cause pitch angle scattering of radiation belt electrons at energies larger than $\sim 100$ keV and up to $\sim 4$ MeV electrons.

The electron precipitation due to EMIC waves during storm time takes place not only on the duskside but propagates to other local times; how the precipitation develops with local time will be investigated in future studies.

Summary and Conclusions

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