Storm Time Ring Current - Atmosphere Interactions: Observations and Modeling

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- Simulate the ring current-atmosphere interactions during the large geomagnetic storm of \textbf{October 21 - 25, 2001} using data from the \textit{MPA} and \textit{SOPA} instruments on \textit{LANL} spacecraft
- Investigate the relative role of a) the convection electric field, b) radial diffusion, and c) wave-particle interactions on the dynamics of energetic particles
- Obtain \textit{H}\(^+\), \textit{He}\(^+\), and \textit{O}\(^+\) ion and \textit{electron} fluxes and study ring current dawn-dusk asymmetry; obtain global images of \textit{EMIC} wave growth and ion precipitation
- Compare model results with \textit{Cluster}, \textit{NOAA}, and \textit{Polar} observations & \textit{Dst} index
- Acquire knowledge needed for the development of an equatorial convection electric field model
An interplanetary shock was observed at ~16 UT on October 21

IMF Bz~20 nT & solar wind speed v~700 km/s; a 2nd negative Bz~15 nT excursion at hour~33

Triggered a large geomagnetic storm with Dst~190 nT; strong geomagnetic activity lasting for about a day with 2nd minimum in Dst~165 nT

Two enhancements of Kp=8- and Kp=7+ occurred at hour~22 and hour~40
• Energy spectra and pitch angle spectra for $H^+$, $He^+$ and $O^+$ in the prenoon sector as the S/C goes toward perigee (4.0 Re)

• The energy spectra clearly show the deep minimum at about 10 keV in all species

At high energies $H^+$ peak @ 90 degrees

Low energy $O^+$ and $He^+$ outflow

In the inner magnetosphere field aligned low energy $O^+$ from both hemispheres

Cluster/CODIF Data: October 21, 2001
The Medium Energy Proton and Electron Detector (MEPED) is an instrument that has been flown on the NOAA series of polar orbiting meteorological satellites.

- Fluxes of locally mirroring ions
  - (a),(b) - 30-80 keV
  - (c),(d) - 80-240 keV
  - (e),(f) - 240-800 keV

- Asymmetric flux enhancement near dusk during the main phase
  - (a), (c), (e) - dawn, MLT=7
  - (b), (d), (f) - dusk, MLT=19

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plasmapause position
Kinetic Model of the Terrestrial Ring Current

\[ \frac{\partial F_t}{\partial t} + \frac{1}{R_o^2} \frac{\partial}{\partial R_o} \left( R_o^2 \left< \frac{dR_o}{dt} \right> F_t \right) + \frac{\partial}{\partial \varphi} \left( \left< \frac{d\varphi}{dt} \right> F_t \right) + \frac{1}{\gamma p} \frac{\partial}{\partial E} \left( \gamma p \left< \frac{dE}{dt} \right> F_t \right) + \]

\[ \frac{1}{h(\mu_o)\mu_o} \frac{\partial}{\partial \mu_o} \left( h(\mu_o)\mu_o \left< \frac{d\mu_o}{dt} \right> F_t \right) = \]

\[ \left< \left( \frac{\partial F_t}{\partial t} \right)_{rd} \right> + \left< \left( \frac{\partial F_t}{\partial t} \right)_{charge\ exchange} \right> + \left< \left( \frac{\partial F_t}{\partial t} \right)_{collis} \right> + \left< \left( \frac{\partial F_t}{\partial t} \right)_{wpi} \right> + \left< \left( \frac{\partial F_t}{\partial t} \right)_{atm} \right> \]

where

\[ \left< \left( \frac{\partial F_t}{\partial t} \right)_{rd} \right> = R_o^2 \frac{\partial}{\partial R_o} \left( \frac{1}{R_o^2} \left< D_{R_o,R_o} \right> \frac{\partial F_t}{\partial R_o} \right) \quad \text{and} \quad \gamma = 1 + \frac{E}{m_o c^2} \]

- \( R_o \) - 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

\[ h(\mu_o) = \frac{1}{2 R_o} \int_{s_m}^{s_s} \frac{ds}{\sqrt{1 - B(s)/B_m}} \]
Equatorial plasmaspheric electron density
Ion composition: 77% H⁺, 20% He⁺, 3% O⁺
Electric potential in the equatorial plane:

- Both models predict strongest fields during the main phase of the storm
- Volland-Stern model is **symmetric** about dawn/dusk by definition
- Weimer model is more **complex** and exhibits variable east-west symmetry and penetrates to lower $L$ shells during active times
Electric field in the equatorial plane during the storm main phase:

- The fields are mapped to the SM magnetic equator for each 4 s using the Tsyganenko magnetic field model; signatures of ULF (Pc5) waves are seen.
- The solid red line indicates 10-min running averages of the data.
- **Weimer** model reproduces very well the radial component but not the azimuthal electric field component.
Model H⁺ Comparison with CLUSTER/CIS Data

- Volland-Stern model underestimates the distribution within the stagnation dip at low $L$
Model Comparison with Polar/MICS Data: Main Phase

V/S Convection  Weimer Convection  Polar/MICS

a) MLT=10.4, MLAT=−57.2, UT=12, Oct 21

b) MLT=9.9, MLAT=−58.4, UT=6, Oct 22
Good agreement at 30 keV near dusk, Weimer model reproduces better the timing of the enhancement at dawn but overestimates the magnitude.
Convective growth rates of EMIC waves are self-consistently calculated using the hot plasma dispersion relation:

$$\frac{\gamma \omega}{V_g} = \Psi(n_t, E_{ll}, A_t)$$

where $n_t$, $E_{ll}$, $A_t$ are calculated with our kinetic model for $H^+$, $He^+$, and $O^+$ ions.

The local growth rates are integrated along wave paths which are field-aligned and extend over ±5° magnetic latitude (±10° at the plasmapause) to obtain the wave gain $G$ (dB).

We calculate the wave amplitude $B_w (nT)$ using:

- $B_w = 10 \times 10^{(G_{\text{max}} - G)/G_{\text{min}}}$ for $G_{\text{min}} < G < G_{\text{max}}$

- $B_w = 10 \text{ nT}$ for $G > G_{\text{max}}$

since the amplitudes of EMIC waves reach saturation values of 10 nT in the inner magnetosphere.
EMIC Waves Excitation and Ion Precipitation

- We calculated the wave growth of EMIC waves from the He\(^+\) band (between O\(^+\) and He\(^+\) gyrofrequency)
- Intense EMIC waves are generated near \textit{Dst} minima and during the recovery phase
- \textbf{Ion precipitation} is significantly enhanced within regions of EMIC wave instability by wave-particle interactions
The $D_{st}$ index is underestimated when the Volland-Stern convection model is used.

Ring current energization is increased during the main phase when the Weimer model is used.

Radial diffusion enhances significantly ring current buildup during the 2nd $D_{st}$ minimum, giving better agreement with observations.
Radial diffusion injects high-energy particles deep into the magnetosphere ($L<4$) and increases the total ring current energy by $\sim 15\%$ near minimum $Dst$.

The electron contribution is small ($\sim 2\%$) during quiet times and reaches maximum values of $\sim 10\%$ near $Dst$ minima.
Conclusions

We simulated ring current (RC) dynamics during the large storm of October 21-25, 2001 and compared results from a) Volland-Stern, and b) Weimer convection electric field models:

• Both models reproduced the enhancement of ~30-80 keV fluxes near dusk seen in NOAA data; the enhancement near dawn was underestimated using a Volland-Stern model
• Weimer model reproduced very well the radial component of the merged Cluster/EDI/EFW electric field; significant differences were seen in the azimuthal component
• The comparison with Polar/MICS and CLUSTER/CIS in-situ data showed good overall agreement with both models; Volland-Stern underestimated the fluxes within the stagnation dip
• Intense EMIC waves were generated during the main and recovery phases; this caused a significant enhancement of the ion precipitation predicted with the model. Scattering by EMIC waves caused about 10% reduction of the total RC energy
• Comparison with Dst index showed:
  - the Dst index was underestimated when the Volland-Stern convection model was used; Weimer model reproduced faster RC buildup and better agreement with observations
  - radial diffusion did not affect RC buildup during the early main phase but increased significantly the total ring current energy during the recovery phase
• Further extensions of this work will consider constructing an equatorial convection electric field model of the inner magnetosphere based on merged EDI and EFW data
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