Electron acceleration by Alfven waves in the magnetosphere

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(image courtesy of NASA)
Magnetosphere-Ionosphere Coupling
Magnetospheric configuration changes drive **Field Aligned Currents (FAC)**.
FACs carry electron flux into ionosphere

Electron flux interacts with atmospheric gases to produce aurora
Poynting and Electron flux also drive outflow of heavy ions which alters the magnetospheric configuration.
Auroral Morphology

- **Monoenergetic Aurora** are associated with
  - quasi-static global Field Aligned Currents
  - Low frequency *A*lfven waves
- **Broadband Aurora** are associated with
  - kinetic scale *A*lfven waves ($\lambda \sim c/\omega_{pe}$, $\rho_s$ or $\rho_i$)
  - and can drive substantial outflow
- **Diffuse Aurora**
  - EMIC and whistler waves (radiation belts).

**Fundamental Questions:**
- How and where are e$^-$ accelerated to carry FACs?
- How does wave energy reach dispersive scales?
- How do auroral arcs form?
- What is feedback on global system?
Characteristics of Monoenergetic and Broadband Aurora

(TSW October 2011)

Reimei Satellite

Electron Pitch Angle

Electron Energy (eV)

66 km

66 km

X 9:31:45.576 UT

X 9:31:52.545 UT

670 nm Max Intensity = 151 kR

670 nm Max Intensity = 103 kR

Electron Energy Flux at Ionosphere (mW/m²)

(Courtesy C. Chaston)
Mono-energetic Aurora and low frequency Alfvén waves
Field Line Resonances (standing Alfven waves) and auroral arcs

FLRs can be generated by mode conversion from fast mode

Field Line Resonance

magnetopause boundary

fast mode

Longitude 340° 330° 340°

Latitude 63° 66°

(Samson et al., 2003)

Long extended arc in azimuthal direction (out of page)

(Samson et al., 2003)

(mHz frequency wave)

(GILL 31/1997 (at Time (UT)=04:26:15)

Power

0 1 2 3 4 5

0.5x10^6 1x10^6 1.5x10^6 2x10^6

V_A(x)

x_r

x_m

x_t

(Samson et al., 2003)
What generates $E_{\parallel}$ in Alfvén waves?

- Dispersive wave effects - (e.g. Wei et al., 1994; Streltsov and Lotko 1996; Bhattacharjee, et al. 1999; Wright et al., 2002).

- Anomalous resistivity (Lysak and Dum, 1983; Lotko et al., 1998).

- Mirror force effects (Rankin et al., 1999).

Need $E_{\parallel}$ to accelerate trapped electrons to carry $j_{\parallel}$

Questions: Can we generate sufficient $E_{\parallel}$ due to mirror force effects in a self-consistent kinetic simulation to accelerate electrons to keV energies? What are signatures of acceleration?
2D hybrid MHD-kinetic electron model

(Damiano et al., Phys. Plasmas, 14, 062904, 2007)

Cold Plasma MHD equations

Momentum equation

\[
\mu_o \rho_o \frac{\partial u_\phi}{\partial t} = \frac{B_o}{h_\parallel h_\phi} \left[ \frac{\partial}{\partial x_\parallel} (h_\phi b_\phi) \right]
\]

Faraday’s Law

\[
\frac{\partial b_\phi}{\partial t} = \frac{-1}{h_\parallel h_\perp} \left[ \frac{\partial}{\partial x_\parallel} (h_\perp E_\perp) - \frac{\partial}{\partial x_\perp} (h_\parallel E_\parallel) \right]
\]

Perpendicular Ohm’s law

\[
E_\perp = -u_\phi B_o
\]

coupling via \(E_\parallel\) (Gen. Ohm’s Law including moments of e\textsuperscript{-} distribution function)

Guiding center equations

\[
m_e \frac{dv_\parallel}{dt} = -eE_\parallel - \mu_m \nabla_\parallel B_0
\]

\[
h_\parallel \frac{dx_\parallel}{dt} = v_\parallel
\]
mirror force term

Particle/field interpolation done using standard PIC techniques.
Initial Perturbation

Half-Gaussian results in only region of upward FAC

Ionospheric boundary at altitude of 1 Re
Feedback in hybrid model

- Perpendicular dispersion ($S_\perp=-E_\parallel b_\phi$)
- Cross scale coupling
Mirror force effects can accelerate electrons to keV energies.

Larger $T_e$ -> increased mirror force trapping -> remaining current carriers must be accelerated to higher velocity.
Electron acceleration is a large sink of wave energy

Significant energy dissipation

Un-driven resonance would completely damp in $< 2 T_A \rightarrow$ same magnitude as Ohmic dissipation in ionospheric currents.
Broadband Aurora and Dispersive Alfven waves
Broadband $e^-$ precipitation correlated with Alfvenic Poynting flux.

Broadband electron energy flux

Downward Alfvenic Poynting flux

Poynting flux associated with $\sim$Hz frequency dispersive Alfven waves ($\lambda_{||} \sim R_E$, $\lambda_\perp \sim \lambda_e$, $\rho_s$, $\rho_i$).

(Wing et al., 2013)

(Keiling et al., 2003)
Broadband aurora increase rapidly at onset (e.g. Wing et al., 2013).

Is dispersive scale structuring imposed at onset site or after?

Breaking of fast flows is one observed source of KAWs (Lessard et al., 2006, 2011)

Wave observations (e.g. Lessard et al., 2006, Chi et al., 2009) used to evaluate onset timing and location.

Understanding transit time of waves to ionosphere is important to help connect optical signatures to driving mechanism.
Characteristics of wave-particle interactions depend on location.

Path along field line is a highly variable plasma environment.

- IAW regime
- Alfven wave
- Fermi acceleration
- KAW regime
- Particle trapping

- Location/mechanism for acceleration not clearly established.
- Means by which energy reaches dispersive scales not known.
- Studies to date, informative but are mostly 1D or local.
- Limited exploration of $\rho_i$ effects ($T_i/T_e \sim 7$ in plasma sheet).
Hybrid gyrofluid-kinetic electron model in curvilinear coordinates

Cold Plasma MHD equations

Modified Momentum equation

\[
\mu_o \rho_o \frac{\partial \tilde{u}_\phi}{\partial t} = \frac{B_o}{h\| h_\phi} \left[ \frac{\partial}{\partial x\|} (h_\phi b_\phi) \right]
\]

where \( \tilde{u}_\phi = (1 - 1.25 \rho_i^2 \nabla^2_\perp) u_\phi \)

Faraday’s Law

\[
\frac{\partial b_\phi}{\partial t} = -\frac{1}{h\| h_\perp} \left[ \frac{\partial}{\partial x\|} (h_\perp E_\perp) - \frac{\partial}{\partial x\perp} (h\| E\|) \right]
\]

Modified Perpendicular Ohm’s law

\[
E_\perp = -B_o (\tilde{u}_\phi - \rho_i^2 \nabla^2_\perp \tilde{u}_\phi)
\]

coupling via \( E\| \) (Gen. Ohm’s Law including moments of e\(^{-}\) distribution function)

Kinetic Alfven wave pulse – initial perturbation example

Initialize KAW perturbation in the plasma sheet

Identical pulses propagate to each field-aligned boundary (at 1 \( R_E \) altitude above Earth surface).

Two simulation cases:
1) \( T_i=0, T_e=100 \) eV
2) \( T_i=1 \) keV, \( T_e=100 \) eV

\[
\frac{k_{\perp}}{k_{||}} \sim 10
\]

\[
\frac{k_{\perp}}{k_{||}} \sim 10 - 100 \quad \text{(Chaston et al., 2014)}
\]

Field line of maximum upward current

\( \lambda_{\perp} \sim 0.1 \) \( R_E \)

perpendicular \( E_{\perp} \) profile at equator
Increased phase speed, but reduced coupling

\[ \omega = k_{\parallel} V_A \sqrt{1 + k_{\perp}^2 \rho_i^2 \left(1 + \frac{T_e}{T_i}\right)} \]

In plasma sheet, \(T_e/T_i \sim 1/7\)

(Baumjohann et al., 1987)

Also evident in 2 fluid analysis
(e.g. Chaston et al., 2003)

\[ \frac{E_{\parallel}}{E_\perp} = \frac{-k_{\parallel} k_{\perp} \rho_s^2}{1 + k_{\perp}^2 \rho_i^2} \]
Electron distribution function evolution

\( \frac{\omega}{k_{\parallel}} = V_A \sim 0.2 \times 10^7 \text{m/s} \)

Parallel elongation in distribution function is qualitatively consistent with observations (e.g. Wygant, 2000) and simulations (Watt and Rankin, 2009)
Superposition at same $l_\parallel = 5 \text{ RE}$, but different times

More perpendicular dispersion for increased $T_i$
$\rho_i$ effects limit current and electron energization all along field line.

**Ionospheric Evolution**

![Graphs showing ionospheric evolution](b.png)
Mirror force effects in global scale Alfven waves self-consistently produce sufficient $\Delta \Phi_{||}$ to accelerate electrons to keV energies (consistent with observations).

Electron acceleration is a significant sink of wave energy.

Consistent with observations, electron acceleration in dispersive scale Alfven waves is broadband in nature.

$\rho_i$ effects significantly shorten transit time of Alfven wave to the ionosphere but reduce the ability of the wave to energize electrons.

$E_{||}$ effects (on all scales) cause a perpendicular dispersion of wave energy.
Summary

- Mirror force effects in global scale Alfven waves self-consistently produce sufficient $\Delta \Phi_{||}$ to accelerate electrons to keV energies (consistent with observations).
- Electron acceleration is a significant sink of wave energy.
- Consistent with observations, electron acceleration in dispersive scale Alfven waves is broadband in nature.
- $\rho_i$ effects significantly shorten transit time of Alfven wave to the ionosphere but reduce the ability of the wave to energize electrons.
- $E_{||}$ effects (on all scales) cause a perpendicular dispersion of wave energy.

**Fundamental Questions:**

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Future directions

• Broadband aurora - parameter study \((k_\perp, k_\parallel, E_\perp, T_i, T_e)\).
• \(\rho_i\) effects on Field Line Resonances - affects \(E_\parallel\) profile (Streltsov et al., 1998) - observed (Chaston et al., 2013).
• Fast mode dynamics and mode conversion (relevant to both Field Line Resonances and broadband aurora) - stretched tail topologies (MAG2D)
• Ionospheric coupling - (ionospheric dissipation, return currents, multi-period simulations \(\rightarrow\) auroral arc formation, evolution)
• Cross-scale coupling of wave energy [phase mixing, wave-wave coupling (nonlinear MHD/3D), wave particle interactions, ionospheric feedback].
• Nonlinear stationary inertial Alfven waves (nonlinear MHD).
• More systematic comparison with satellite observations (e.g FAST, Polar, Themis).
• More realistic driving.
Extra Slides
Generalized Ohm’s Law

\[
\frac{\partial}{\partial x_\perp} \left[ \frac{h_\phi}{h_\parallel h_\perp} \left( \frac{\partial (h_\parallel E_\parallel)}{\partial x_\perp} \right) \right] - \frac{h_\parallel E_\parallel}{\lambda_e^2} = \frac{\partial}{\partial x_\perp} \left( \frac{h_\phi}{h_\parallel h_\perp} \frac{\partial}{\partial x_\parallel} (h_\perp E_\perp) \right)
\]

\[+ \quad e \mu_0 \frac{\partial}{\partial x_\parallel} \int v_\parallel^2 f_e d^3v \]

\[+ \quad \mu_o \frac{e}{m_e} \frac{\partial B_0}{\partial x_\parallel} \int \mu_m f_e d^3v \]

\[- \quad 2\mu_o \frac{e}{m_e} \frac{\partial B_0}{\partial x_\parallel} \int \frac{m_e v_\parallel^2}{2B_0} f_e d^3v \]

KAW

Mirror force terms

Moments of electron distribution function determined from kinetic electrons using Particle-In-Cell (PIC) techniques.

(plus auxiliary Poisson’s equation to enforce quasi-neutrality)

(Damiano et al., Phys. Plasmas, 14, 062904, 2007)