Ionospheric Outflow and Magnetosphere-Ionosphere Coupling

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TOPICS

- Physics of ion escape
- Regulation of outflow
- Impacts on M-I system
  - Stormtime outflows
Outflow Physics

guiding center equations \( (\varepsilon \sim v_\perp/\omega_c \ell \sim 1/\omega_c \tau \ll 1) \)

\[
\frac{d\mathbf{v}_\parallel}{dt} = \frac{eE_\parallel}{m} - \mu \nabla B + \mathbf{v}_E \cdot D_t \mathbf{b} - \mathbf{g} \cdot \mathbf{b} - v_c v_\parallel
\]

- ambipolar field
- centrifugal force
- collisional drag

\[
\begin{align*}
D_t \mu &= 0 \\

where \quad \mu &= \frac{\nu_0^2}{2B}
\end{align*}
\]

\[
D_t \equiv \frac{\partial}{\partial t} + (v_\parallel \mathbf{b} + \mathbf{v}_E) \cdot \nabla, \quad \mathbf{v}_E = \frac{\mathbf{E} \times \mathbf{b}}{B}
\]

- mirror force
- gravity

(ponderomotive)
Polar Wind

Hydrostatic Equilibrium

\[ 0 = -\nabla_{\parallel} P_{O} + e n_{O} E_{\parallel} - n_{O} m_{O} \mathbf{g} \cdot \mathbf{b} \]

\[ \downarrow \quad 0 = -\nabla_{\parallel} P_{e} - n e E_{\parallel} \]

\[ 0 = -\frac{d(P_{O} + P_{e})}{dr} - n_{O} m_{O} g \frac{R_{E}^{2}}{r^{2}} \]

\[ \downarrow \quad P_{O,e} = n_{O,e} T_{O,e}, \quad T_{O,e} = \text{const} \quad r = R_{E} + h \]

\[ n = n_{*} e^{-(h-h_{*})/H}, \quad H = k(T_{O} + T_{e})/m_{O} g \]
Polar Wind

Add light ions

\[ \frac{dv_{||}}{dt} = \frac{eE_{||}}{m} - m\vec{g} \cdot \vec{b} - v_c v_{||} \]

Banks and Holzer 1968

Dynamic Equilibrium

\[ n_S \frac{du_{S ||}}{dt} = \left[ en_S E_{||} - \nabla_{||} P_S \right] / m_S \]

\[ - n_S \vec{g} \cdot \vec{b} - v_c u_{S ||} \]

\[ \nabla_{||} \left( n_S u_{S ||} / B \right) = 0 \]

\[ \nabla_{||} P_e + enE_{||} = 0 \]
Transverse acceleration → mirror force

\[ \frac{dv_{||}}{dt} = -\mu \nabla_{||} B - \vec{g} \cdot \vec{b} - \nu_{e} v_{||} \]

Bouhram et al. '04
Centrifugal (Ponderomotive)

\[
\frac{d\mathbf{v}_e}{dt} = \mathbf{v}_e \cdot \mathbf{D}_p \mathbf{b} - \mathbf{g} \cdot \mathbf{b} - v_e v_e
\]

Streltsov and Lotko 2008
Ponderomotive + $\perp$-Acceleration

\[
\frac{dv_\parallel}{dt} = -\mu \nabla \cdot B + \vec{v}_e \cdot D \vec{b} - m - \nu v_\parallel
\]

Paschmann et al. ‘03
Cusp Outflow

- Enhanced ionization
- Joule Heat
- Electron precipitation
- Poynting flux

$\Rightarrow$ $\mathrm{O^+}$ outflow

cf. Strangeway et al. ’05
Causal Relations

ION OUTFLOW

POYNTING FLUX

ELF/VLF WAVES (heating)

ION UPWELLING

ION SCALE HEIGHT INCREASE

JOULE DISSIPATION

CONVECTIVE TRANSPORT

ELECTRON SCALE HEIGHT INCREASE (ambipolar field)

ELECTRON HEATING IONIZATION

ELECTRON PRECIPITATION

0.721

0.755

0.634

0.743

0.741

0.888

Strangeway et al. 05
Magnetospheric dynamo
(≈ geomagnetically fixed)
+
Convective plasma surge
⇓
Outflow surge

Sondrestrom ISR 11 Feb 2002

Semeter et al. '03

Semeter et al. 03
Impacts of Outflows on MI System

- Plasmasheet composition
- Ring current
- Reconnection rate
- Kelvin-Helmholtz Instability at MP
- Radbelt energization and loss
- Cross polar cap potential
  - precipitation
  - Joule heat
**$O^+ \text{ Plasmasheet}$**

**Plasmasheet**
- Normally $H^+$ dominant
- $O^+$-rich during storms
  - $O^+$ injections from Cusp fountain
  - Nightside BPS

**Stormtime substorms**
- $H^+$ is swept away
- Leaving $O^+$ dominant pressure and density
- Earthward injected $O^+$ dominates ring current

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Kistler et al. 2005
Ring Current and Plasma Sheet Composition

![Graph showing the relationship between O^+ / H^+ and DST or SYM-H, nT. The graph includes data from various studies and events, such as 2003/10/30 and 1994/01-2003/05.]

Numbers 1 to 8 correspond to:
1. Gloeckler et al. '85
2. Krimigis et al. '85
3. Hamilton et al. '88
4. Feldstein et al. '00
5. Greenspan & Hamilton '02
6. Roeder et al. '96
7. Daglis et al. '97
8. Daglis et al. '00

Caption: Nosé et al. 2005
Density fraction: $n_h = 0.39 \ n_e$

Heavy ions reduce reconnection rate by 50%
Instability criterion: \[ |\Delta V_M| > V_{A*} \equiv \left( \frac{B_{M,sh}^2 + B_{M,sp}^2}{\mu_0 \rho_*} \right)^{1/2} \], \quad \rho_* \equiv \frac{\rho_{sh} \rho_{sp}}{\rho_{sh} + \rho_{sp}}
Wave emissions depend on plasma conditions:
- cold plasma density
- mass composition
Cross-Polar Cap Potential

inertial loading

Winglee et al. 2002

Cross-Polar Cap Potential

Variable O$^+$ Concentration

$\text{n}_O/\text{n}_H$

0.05, 0.10, 0.25, 0.50, 1.00

$100 \text{ cm}^{-3}$

$400 \text{ cm}^{-3}$

$300$

$200$

$100$

$\text{AMIE}$

Sep 24

Sep 25

Winglee et al. 2002
LFM Global Simulation
7-8 Nov 2004 Storm

- One-Fluid
- “Strangeway” outflow
- Compare results w/ and w/o outflow
- Main focus: MI coupling characteristics
LFM Global MHD Model equations

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0 \]

\[ \rho \frac{\partial \vec{u}}{\partial t} + \rho \vec{u} \cdot \nabla \vec{u} + \nabla p = \vec{J} \times \vec{B} \]

\[ \frac{\partial \varepsilon}{\partial t} + \nabla \cdot (\varepsilon + p) \vec{u} = \vec{J} \cdot \vec{E} \]

\[ \vec{E} + \vec{u} \times \vec{B} = 0 \]

\[ \varepsilon = \frac{\rho |\vec{u}|^2}{2} + \frac{p}{\gamma - 1} \]

\[ \frac{\partial \vec{B}}{\partial t} + \nabla \times \vec{E} = 0 \]

\[ \mu \vec{J} = \nabla \times \vec{B} \]
LFM Grid

53x48x64
Ionospheric Grid

> 200 km grid resolution (typical)

⇒ Small-scale Alfvén waves are not resolved
Empirical Model for Ionospheric Outflow

FAST data near 4000-km altitude in the low-altitude cusp

Strangeway et al. 05; Zheng et al. 05

Ion Flux vs. Poynting Flux

\[ F_{\parallel \parallel} = 10^{7.33} S_{\parallel}^{1.265} \]

\[ 10^{6.84} S_{\parallel}^{0.535} \]

\[ r = 0.721 \]

Ion Flux vs. Electron Flux

\[ F_{\parallel \parallel} = 10^{-11.52} F_{e}^{2.275} \]

\[ r = 0.755 \]
EM Input Power

LFM $S_{||}$

Empirical Formula

$F_{H||}$

Source-Weighted $F_{H||}$

Auroral/Cusp Outflow

LFM $F_{e||}$

Source “Regions”

Source “Regions”

Calibrate Fluence

Constant $V_{||}$

OUTFLOW ALGORITHM

0 $\rightarrow$ 1

Minimum $(F_{e||}/F_{s}, 1)$

50 km/s

BC
7-8 Nov 2004
Superstorm

SW / IMF Conditions

Tsurutani et al. 2008
MI Interaction
7-8 Nov 2004

REGULATION
- IMF $B_z$ (primary)
- SW $P_{\text{dyn}}$

OUTFLOW
- Enhances $P_{||e}$
- Reduces $I_{||}$, $P_J$
- Mixed effect on $\Phi_{PC}$
Outflows from Northern and Southern Hemispheres

Fluence $10^{27}/s$

Ion flux, $10^{10}/cm^2$-s

Bz

UT, hours

07 Nov 2004

08 Nov 2004
OUTFLOW PROPERTIES

- Large fluxes, fluences at storm peak
- Largest in the dayside
- Not confined to cusp
- SW $P_{\text{dyn}}$ and IMF $B_z$ regulate outflow fluxes
- Poynting flux, outflow are largest in summer hemisphere

Fluence $8.9 \times 10^{27}$ ions/s

7 Nov 2004

20:30 UT
OUTFLOW EFFECTS

- More extended, denser plasmasheet
- Plasma accumulation in inner magnetosphere
- Magnetopause moves outward

Moderate $B_z < 0$  
Large $P_{dyn}$ increase  
Magnetic cloud impact $B_z < 0$  
Cloud ends  

7-8 Nov 2008 Storm  
GSM Equatorial Plane  

with outflow
Cross-Polar Cap Potential

Winglee et al. 2002

Variable O⁺ Concentration

n₀/n_H = 0.05
100 cm⁻³
400 cm⁻³

Potential, kV

Sep 24 00 01 02 03
Sep 25

AMIE

n₀/n_H
0.05
0.10
0.25
0.50
1.00

Winglee et al. 2002
MI Interaction
7-8 Nov 2004

REGULATION
- IMF $B_z$ (primary)
- SW $P_{dyn}$

OUTFLOW
- Enhances $P_{\parallel e}$
- Reduces $I_{\parallel}$, $P_J$
- Mixed effect on $\Phi_{PC}$
LFM Precipitation Algorithm

**MHD Variables**
- \( \rho \)
- \( \mathbf{v} \)
- \( P \)
- \( B \)

**“Drizzle” Energy**
\[
\varepsilon_0 = c_1 \frac{P}{\rho}
\]

**“Beam” Energy**
\[
\varepsilon_\parallel = c_2 \frac{J_\parallel \varepsilon_0^{1/2}}{\rho}
\]

**Precipitating Electron Flux**
\[
F_{\parallel} = c_3 \rho \varepsilon_0^{1/2} \times \left[ 8 - 7 \exp\left(-\varepsilon_\parallel/\varepsilon_0\right) \right]
\]

**Electron Energy**
\[
\varepsilon_e = \varepsilon_0 + \varepsilon_\parallel
\]

**“Robinson” Conductivity**
\[
\Sigma_p = \frac{5\varepsilon^{3/2} F_{\parallel}^{1/2}}{1 + \varepsilon^2/16}
\]
\[
\Sigma_H = 0.45\varepsilon^{0.85} \Sigma_p
\]

\[
\nabla \cdot \Sigma \cdot \nabla \Phi_i = -J_{\parallel i}
\]

\[
\nabla \cdot \Sigma \cdot \nabla \Phi_i = -J_{\parallel i}
\]
Feedback: Outflow with Precipitation

**MHD Variables**
- $\rho$
- $v$
- $P$
- $B$

**Drizzle Energy**
\[ \varepsilon_0 = c_1 \frac{P}{\rho} \]

**Beam Energy**
\[ \varepsilon_\parallel = c_2 \frac{J \varepsilon_0^{1/2}}{\rho} \]

**Precipitating Electron Flux**
\[ F_{e\parallel} = c_3 \rho \varepsilon_0^{1/2} \times \left[ 8 - 7 \exp\left( -\varepsilon_\parallel / \varepsilon_0 \right) \right] \]

**Electron Energy**
\[ \varepsilon_e = \varepsilon_0 + \varepsilon_\parallel \]

**Vortex Instability**
\[ \nabla \cdot \vec{\Sigma} \cdot \nabla \Phi_i = -J_{\parallel i} \]

**Auroral/Cusp Outflow**
\[ F_{i\parallel} \left( E \times B, F_{e\parallel}, \cdots \right) \]

**“Robinson” Conductivity**
\[ \Sigma_p = \frac{5 \varepsilon^{3/2} F_{e\parallel}^{1/2}}{1 + \varepsilon^2 / 16} \]
\[ \Sigma_H = 0.45 \varepsilon^{0.85} \Sigma_p \]
Feedback: Outflow w/o Precipitation

MHD Variables

\( \rho \)

\( \mathbf{v} \)

\( P \)

\( \mathbf{B} \)

Polar Wind Outflow

\[ F_{s||}(P_s, \cdots) \]
Simulation Issues

– Superfluent outflows *but* DC Poynting flux alone is too indiscriminate in regulating outflow

  Model subgrid energization processes

– Outflows influence electron precipitation properties ⇒ conductances ⇒ electrodynamics

  Much better precipitation models needed
Summary

- Physics of ion escape is well developed
- Processes regulating outflow rate not well understood

Outflows impact
- Reconnection rates
- Storm dynamics
- Rad Belt dynamics
- MI interaction (precip, FAC, Joule heat, PC potential)

FEEDBACK between outflow-induced density enhancements and electron precipitation, conductivity
Extra Slides
Cusp
“Heating Wall”
Knudsen et al. 1994

Altitude, km

~3.5 RE

Ionospheric Source

Turbulent Fields

Ion Heating

Satellite

Adiabatic Transport

Ion Fountain

Convection

ΔΔ~1–2°

Mag Latitude
Ionospheric Potential

$\nabla \cdot \Sigma \cdot \nabla \Phi_i = -J_{||i}$
EM Input Power

LFM $S_{||}$

Empirical Formula

Strangeway

$F_{H||}$

Source-Weighted $F_{H||}$

Auroral/Cusp Outflow

Source “Regions”

$F_{e||}$

Minimum $(F_{e||}/F_{s||} 1)$

$V_{||}$

$\sim 10^{25} \#/s$

$50 \text{ km/s}$

Calibrate Fluence

$BC$

OUTFLOW ALGORITHM
Model extensions
7-8 Nov 2008 Storm

No outflow

Moderate $B_z < 0$
Large $P_{\text{dyn}}$ increase
Magnetic cloud impact
Cloud ends

GSM Equatorial Plane

with outflow

7 Nov 15:00 – 17:00
7 Nov 18:00
7 Nov 20:10
8 Nov 12:10
7-8 Nov 2008 Storm

- No outflow

Noon-Midnight Projection

- 7-8 Nov 2008 Storm Noon-Midnight Projection
- Moderate $B_z < 0$
- Large $P_{dyn}$ increase
- Magnetic cloud impact
- Cloud ends

- 7 Nov 15:00 – 17:00
- 7 Nov 18:00
- 7 Nov 20:10
- 8 Nov 12:10
Observational Statistics
(Yau and André 97; Cully et al. 03; Lennartsson et al. 04)

- Outflow fluence increases
  - at higher altitude
  - for southward IMF
  - with greater SW $P_{\text{dyn}}$

- Outflow energy increases
  - at higher altitude
  - with greater SW $P_{\text{dyn}}$

- 1-100 GW / hemisphere required to power the H$^+$ outflow

Polar ions: 15 eV – 33 keV
AC Poynting Flux
(and the effect of $\Delta \Phi_{\parallel}$)

- Morphology
- Amplitude
- Phase

\[
S_{\parallel} = \frac{\delta E \times \delta B}{\mu_0} \cdot \hat{b}_0
\]

Poynting Flux, 6-180 s Filter

Keiling et al. 03
January – December, 1997

9 May 1997, 08:15-08:55 UT

Bandpass Filtered $S_{\parallel}$

at 73 ILAT, 20:30 MLT, $R = 3.5 R_E$

6-180 s

6-360 s

6-540 s

6-720 s

6-900 s

UT on May 9, 1997
Sampling Statistics for Empirical Outflow Relations

FAST \approx 4000 \text{ km altitude}

33 orbits, 24-25 Sep 1998 storm  
*Strangeway et al. 2005*

Polar \approx 6000 \text{ km altitude}

37 outflow events, during year 2000  
*Zheng et al. 2005*