Heliophysics in Atmospheres

Thermosphere-Ionosphere Response to Geomagnetic Storms

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Atmospheres

• Gravitationally bound
• Collision dominated - kinetic theory
• Partially ionized < 1% (100-600km altitude)
• Magnetic field - 99% invariant on short timescales
M-I Coupling

- Magnetosphere interacts with the thermosphere/ionosphere through electrodynamics (conductivity, currents, electric fields) and mass flux
- Current system connecting the ionosphere and magnetosphere
- Electromagnetic energy flow (Poynting flux) - normally downward, spatially there can be regions of upward flux
- Joule heating + kinetic energy
- Recovery - flywheel effect, ionosphere/thermosphere as a generator - flux upward
- Mass flux: particle precipitation and outflow, also carries field-aligned current
- Alfven waves - communicates imbalance between M-I
Energy Flow

magnetospheric energy
500 - 1000 GW

- particle precipitation 20%
  - heat, ionization, airglow e.g. auroral illumination
  - Joule heating $\mathbf{J} \cdot (\mathbf{E} + \mathbf{U} \times \mathbf{B})$
    - 80%
      - heat, pressure gradients, winds, etc.

electromagnetic energy 80%

- kinetic energy
  - 20%
    - Ion drag drives neutral winds

- heat, ionization, airglow e.g. auroral illumination

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Pedersen and Hall Conductivity

![Graph showing ion number density and conductivity vs. altitude](image)

- Ion Number Density (cm\(^{-3}\))
- Altitude (km)
- Conductivity (Sm\(^{-1}\))

Legend:
- \(\sigma_p\) (Night)
- \(\sigma_p\) (Day)
- \(\sigma_h\) (Night)
- \(\sigma_h\) (Day)

Electron Density (#/cm\(^3\))

- Ionosphere
- F2
- F1
- D
- E

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Thermosphere-Ionosphere Responses to Magnetospheric Sources

- Auroral precipitation enhances conductivity at high latitudes
- Magnetospheric electric fields enhances plasma transport at high latitudes
- Magnetospheric penetration electric fields imposed globally in less than a second
- Ion drag drives high latitude wind system up to ~ 1 km/s
- Joule and particle energy heats atmosphere
- Thermal expansion, horizontal pressure gradients, equatorward wind surges
- Changes in global circulation
- Neutral composition changes
- Disturbance dynamo
- Positive and negative ionospheric storm phases
Magnetospheric Storm Forcing

TIROS/NOAA auroral precipitation patterns driven by power index:

Weimer electric field patterns driven by solar wind data:

Penetration E-field from High Latitude Magnetospheric Currents

plus SAPS

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Ion motion

- Coulomb force - $e \mathbf{E}$
- Lorentz force - $e \mathbf{V} \times \mathbf{B}$
- Collisions with neutrals - $m \nu (V-U)$,
- Gravity
Ion drift:
Above ~160 km ExB
Below 160 km as collision with neutral atmosphere become more important ion drift rotates towards the E-field vector and reduces in magnitude
Ion-neutral collisions in upper thermosphere frequent enough to drive high velocity neutral wind

Neutral Winds and Temperature: 300 km altitude

Maximum wind speed observed by DE-2 ~ 1400 m/s

ExB ion drift and NmF2
Polar Thermospheric Winds

Fig. 1. Averaged DE 2 thermospheric neutral wind maps for December solstice, solar maximum conditions in geomagnetic coordinates during periods of $K_p \leq 3$ for (a) northern and (b) southern high-latitude regions and periods of $3+ \leq K_p \leq 6$ for (c) northern and (d) southern high-latitude regions.
Non-linear effects

- Compare with hurricane speeds:
  - 150 mph $\equiv 60$ m/s
  - 1500 mph $\equiv 600$ m/s
- Transport/advection and acceleration terms are strong
- Asymmetry in response in dawn and dusk sectors
- Inertial motion on a non-rotating sphere is a great circle
- Spherical co-ords e.g. east/west, is not cartesian system
- Introduces “curvature” terms
- Inertial oscillation
Equations of Motion in pressure coordinates

\[ \frac{\partial}{\partial t} \phi - \frac{\partial}{\partial \theta} V_\phi - \frac{\partial}{\partial \phi} V_\phi - g \frac{\partial}{\partial p} h - \left( 2 \Omega + \frac{V_\phi}{r \sin \theta} \right) V_\theta \cos \theta + g \frac{\partial}{\partial p} \left[ \left( \mu_m + \mu_T \right) \frac{p}{H} \frac{\partial}{\partial p} V_\phi \right] - v_v \left( V_\phi - U_\phi \right) \]

advection pressure Coriolis viscosity ion drag

\[ \frac{1}{p} \frac{\partial}{\partial \theta} p = - \frac{g}{RT} \quad V_z = \left( \frac{\partial}{\partial t} \right)_p - \frac{\omega}{\rho g} \quad \frac{\partial}{\partial p} = - \nabla_p \cdot \overline{V} \]
Inertial Oscillation: balance between centrifugal (curvature) and Coriolis

\[ \frac{V^2}{R} = -fV \]

Radius of curvature \( R = 20^\circ \) latitude
Coriolis high latitude \( f = 1.4 \times 10^{-4} \)
\( V \sim 300 \text{ m/s}, \) convergent if slower, divergent if stronger
Inertial Resonance

- Coriolis force directs winds towards the right in the northern hemisphere
- Tends to move parcels of gas in clockwise vortex, similar to dusk plasma convection cell
- In dusk sector Coriolis tends to constrain parcels within curvature of auroral oval
- In dawn sector gas tends to be expelled equatorward
- Gas constrained within auroral oval can be accelerated to high velocities
- Dawn sector momentum spread over wider area.
Dawn Cell: centrifugal (curvature) and Coriolis assist
⇒ low pressure cell

\[ \frac{V^2}{R} + fV = -\frac{1}{\rho} \frac{\partial p}{\partial n} \]

Vortex in dawn cell always divergent if ion-drag forcing is cyclonic (anti-clockwise)
Storm-time neutral winds produce dynamically driven “holes”

Dawn cell always divergent - typically see density hole
Dusk cell only divergent when wind speeds exceed 300 or 400 m/s
Neutral density holes - dynamically driven?
Ion Motion perpendicular to B

\[ \Omega / \nu_{in} < 1 \quad \vec{V}_i^\perp \approx \vec{F}^\perp \]

\[ \Omega / \nu_{in} > 1 \quad \vec{V}_i^\perp \approx \nu_{in} / \Omega \vec{F} \times \hat{b} \]

\[ \vec{V} = \frac{e}{mv} \vec{E} \]

\[ \vec{V} = \frac{\vec{E} \times \vec{B}}{B^2} \]

Electron Motion

\[ \vec{V} = \vec{U} \]

\[ \vec{V} = \frac{\nu}{\Omega} \vec{U} \times \hat{b} \]
Altitude Dependence: balance of forces change with altitude

300km: 515 m/s
160km: 311 m/s
135km: 359 m/s
120km: 250 m/s
110km: 82 m/s
103km: 23 m/s
Simulation of long-lived vortex in lower thermosphere (140 km)

12 hour generic storm forcing

recovery
Joule heating: $J \cdot (E + V \times B)$

Large temperature and circulation changes in the upper thermosphere

quiet

disturbed
Neutral wind response to “simple” storm

Generic model storm forcing: 30 minute ramp up to activity level 10, and solar wind conditions consistent with Kp 6, 11.5 hrs at elevated storm levels, 30 minute ramp down to quiet for 12 hrs
Equatorward wind at mid latitudes with inclined magnetic field pushes plasma upward along the magnetic field direction to regions of different neutral composition.
Wind effect on ionosphere at mid-latitudes with inclined magnetic field

- Equatorward wind pushes plasma upward in the direction of the geomagnetic field to regions of less molecular species $\text{N}_2$ and $\text{O}_2$, slowing loss rates, and driving a “positive phase” in the ionosphere

- Thermal expansion creates a vertical wind which can also push plasma along an inclined magnetic field to higher altitudes
A few basics on neutral composition change

- Hydrostatic equilibrium is not the same as diffusive equilibrium
- Heating the gas and thermal expansion change the ratio of neutral species (O/N$_2$) on height levels
- Heating and thermal expansion does not change the ratio of neutral species (O/N$_2$) on pressure surfaces
- Pressure surfaces are important because they represent layers of constant optical depth or level of deposition of an ionizing photon or electron
- “Real” changes in neutral composition is caused by upwelling through pressure surfaces, which is driven by divergence of horizontal winds
Global circulation

- Solar driven circulation, quiet conditions (kp = 0)
- Quiet conditions (kp = 2+)
- Perturbed conditions (kp = 7)

Araujo-Pradere et al
Global neutral composition structure looks more like equinox as high latitude heating begins to dominate.

GUVI O/N2
April 14, 2002

Ratio of height integrated O and N₂

GUVI O/N2
April 18, 2002

GUVI/TIMED

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Composition transport at solstice
At mid-latitudes: can be high correlation between composition changes and ion density.

Increase in $N_2$ leads to ionospheric depletion.

Observations and Modeling
Neutral composition and positive and negative ionospheric phases

Prölss 1997
Seasonal/local time variation in ionospheric response at mid-latitudes
Rodger et al. 1989

- Negative phase peaks in summer
- Positive phase peaks in winter
- Negative phase peaks at dawn
- Positive phase peaks at dusk
- Response to summer/winter seasonal circulation and poleward/equatorward diurnal wind variation

(southern hemisphere mid-latitude station)
Low latitude ionosphere strongly influenced by electrodynamics

- What is the relative importance and lifetime of penetration and dynamo electric fields during the different phases of a storm on the day and nightside, and how do they interact?

Figure 6. Schematic of the competing effect of the downward field-aligned diffusion and the upward movement of the plasma produced by an equatorward neutral wind at mid latitudes.

Figure 10. The total electron content (TEC) between altitudes 100 and 2000 km from the SuperPib result at 23:30 UT (18:50 LT) at -70° geographic longitude on the pre-storm day (thin gray line), case 1 (bold gray line), case 2 (thin black line), and the case 3 (bold black line).
Jicamarca vertical drift
Nov 9-10, 2004
CTIPe simulation of disturbance dynamo
Storm-Time Electrodynamics: disturbance dynamo

Blanc and Richmond (1980) theory:

- Equatorward winds drive zonal winds at mid-latitude through the action of the Coriolis force
- Zonal winds $\rightarrow$ equatorward Pedersen current
- Equatorward wind $\rightarrow$ equatorward Hall current
- Positive charge builds up at the equator producing a poleward directed electric field which balance the wind driven equatorward current
- Eastward Hall current causes +ve charge build up at the dusk terminator and -ve charge build-up at dawn
- Reverse $S_q$

\[
J_\theta u = -\frac{\sigma_1}{\sin I} u_\phi B + \sigma_2 u_\theta B \\
J_\phi u = \sigma_1 \sin I u_\theta B + \sigma_2 u_\phi B \\
J_{\theta E} = \frac{\sigma_1}{\sin I} E_\epsilon + \frac{\sigma_2}{\sin I} E_\phi \\
J_{\phi E} = -\sigma_2 E_\epsilon + \sigma_1 E_\phi
\]
CHAMP (400 km) OSEC: Halloween
Mannucci et al. 2005
Ionospheric Irregularities

Dense Plasma

gXB ion drift

B-Field

Gravity

Polarization

E-Field

ExB Drift

Less Dense Plasma

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Plasma Bubble Evolution

Mesoscale Model
Describes temporal development of plasma structure
Uses nonlinear continuity and momentum equations
Includes self-consistent electric fields
Coupled to ambient background
Estimates spectrum of density fluctuations

Retterer (1999)
Summary: main points

• A multitude of processes are operating in the thermosphere-ionosphere during a geomagnetic storm
• Electromagnetic energy is the dominant source at high latitude
• Neutral dynamic response influence the dissipation and is the conduit for many of the changes that occur in the upper atmosphere during a geomagnetic storm
• At high latitudes, large in-track neutral winds and neutral density holes influence satellite drag
• Neutral composition responds to the storm-time circulation and impacts the ionosphere at mid-latitudes
• Electrodynamic forcing also important at mid and low latitudes - prompt penetration and disturbance dynamo
• We understand many of the physical processes, but their relative importance during the various phases of a storm has yet to be elucidated