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Ionosphere-Thermosphere Basics: Dynamics and Energetics

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Ionosphere-Thermosphere Basics IV

Ionospheric Dynamics and Energetics

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Ionosphere-Thermosphere Basics IV

Ionospheric Dynamics and Energetics

1. Equations of force balance – Conservation of momentum
    - Discussion of forces on ions and electrons
        - Pressure gradient
        - Gravity
        - Collisions
        - Electric Fields
        - Lorentz Force
    - Reduce discussion to neutral winds, electric fields and Lorentz force

2. Motions Parallel and Perpendicular to B
    - Mobilities and conductivities

3. Conductivity Profiles
    - Important regions
        - E and F regions and layer conductivities

4. Current Continuity
    - Relation between Jperp and Jparl
    - Polarization electric fields
    - Dynamo equations
        - Jparl as given input neglect winds — high latitude case.
        - Winds as given input Jparl=0 — low mid latitude case

Ionosphere-Thermosphere Basics IV

Ionospheric Dynamics and Energetics

5. Electric fields at low and middle latitudes
    - Drifts perpendicular to B in the meridian (Vperp at equator)
    - Plasma motions including diffusion
        - Fountain effect and horizontal transport
        - Effects of different E-fields
            - Appleton anomaly
            - Reduction of Ion drag
            - Change in layer thickness during the day
            - Reduction in recombination rate at night.
    - Drifts perpendicular to B and perpendicular to the meridian (e-w drifts)
        - Change in effective length of the day for plasma
        - Superrotation of the ionosphere.

6. Plasma motions parallel to B at low and middle latitudes
    - Effects of neutral winds
        - Importance of magnetic dip angle
        - Seasonal asymmetries
        - Changes in Ion composition and number density
        - Effects on plasma temperatures.

Principles of Ionospheric Dynamics

Forces on Charged Particles

- **Collisions with neutral particles.**
    - **Tidal oscillations that propagate up from below.**
    - **In-situ circulation due to high-latitude energetic particles, Joule heating, and local heating from the sun.**
- **Collisions with charged particles.**
    - **Neglect for ions in the ionosphere. Important for electron mobility parallel to B.**
    - **Effective resistivity in the magnetosphere.**
- **Electric Fields**
    - **Externally applied from solar wind sources.**
    - **Internally produced to make total current divergence free.**
- **Lorentz Force**
    - **A charged particle in motion feels a force in a uniform magnetic field.**
- **Gravity**
    - **Most important for ions in the ionosphere**
- **Pressure Gradient**
    - **Perpendicular to the magnetic field dependent on the particle energy distribution.**
    - **Parallel to the magnetic field it produces an ambipolar electric field to make ions and electrons move together.**

Principles of Ionospheric Dynamics

Conservation of Momentum in steady state yields

$$0 = -\frac{1}{N_i}\nabla N_i kT_i \;+\; m_i\vec{g} \;+\; e\left(\vec{E} \;+\; \vec{V}_i \times \vec{B}\right) \;-\; m_i\upsilon_{in}\left(\vec{V}_i - \vec{U}\right)$$

Pressure Gradient **Gravity** **Electric Field** **Lorentz** **Collisions with Neutrals**

How to find V ?

Separate terms that are dependent on V from those that are not.

For ions we get….

$$0 = \underbrace{-\frac{1}{N_i}\nabla N_i kT_i \;+\; m_i\vec{g} \;+\; e\vec{E} \;+\; m_i\upsilon_{in}\vec{U}}_{\textbf{Velocity Independent Forces}} \;+\; \mathrm{e}\vec{V}_i \times \vec{B} \;-\; m_i\upsilon_{in}\vec{V}_i$$

In the rest frame of the neutral gas

$$\vec{V}' = \vec{V} - \vec{U}$$

$$\vec{E}' = \vec{E} + \vec{U} \times \vec{B}$$

$$0 = \overbrace{-\frac{1}{N_i}\nabla N_i kT_i \;+\; m_i\vec{g} \;+\; e\vec{E}'} \;+\; \mathrm{e}\vec{V}_i' \times \vec{B} \;-\; m_i\upsilon_{in}\vec{V}_i'$$

Principles of Ionospheric Dynamics

Conservation of momentum can be written as

$$\mathbf{F} \pm e\left(\mathbf{V} \times \mathbf{B}\right) - m\upsilon\mathbf{V} = 0$$

We solve this equation to determine the particle velocity perpendicular and parallel to the magnetic field resulting from a force F.

Parallel to the magnetic field

$$\mathbf{F}_{\|} - m\upsilon\mathbf{V}_{\|} = 0$$

$$\mathbf{V}_{\|} = \frac{\omega_B}{\upsilon}\frac{1}{eB}\mathbf{F}_{\|}$$

$$\mathbf{V}_{\|} = \kappa_{\|}\mathbf{F}_{\|}$$

The coefficient in relating the velocity to the force is called the “mobility” κ

The particle velocity is proportional to the component of the force parallel to B but may be reduced by collisions between the charged particle and the neutral gas.

Notice MAY be reduced. This will not be true if the force itself is due to collisions with the neutral gas.

Principles of Ionospheric Dynamics

Conservation of momentum can be written as

$$\mathbf{F} \pm e\left(\mathbf{V}\times\mathbf{B}\right) - m\upsilon\mathbf{V} = 0$$

Perpendicular to the magnetic field the situation is more complicated and we proceed as follows

$$\mathbf{F}_\perp \pm e\left(\mathbf{V}_\perp\times\mathbf{B}\right) - m\upsilon\mathbf{V}_\perp = 0$$

$$\frac{e}{m\upsilon}\mathbf{F}_\perp\times\mathbf{B} \pm \frac{e^2}{m\upsilon}\left(\mathbf{V}_\perp\times\mathbf{B}\right)\times\mathbf{B} - e\mathbf{V}_\perp\times\mathbf{B} = 0 \qquad \omega_B = \frac{eB}{m}$$

$$\mathbf{F}_\perp \pm \left(\frac{e}{m\upsilon}\mathbf{F}_\perp\times\mathbf{B} \pm \frac{e^2}{m\upsilon}\left(\mathbf{V}_\perp\times\mathbf{B}\right)\times\mathbf{B}\right) - m\upsilon\mathbf{V}_\perp = 0$$

$$\frac{\upsilon}{m}\mathbf{F}_\perp \pm \left(\frac{eB}{m^2}\mathbf{F}_\perp\times\hat{\mathbf{b}} \mp \omega_B^2\mathbf{V}_\perp\right) - \upsilon^2\mathbf{V}_\perp = 0$$

$$\mathbf{V}_\perp = \frac{1}{\upsilon^2+\omega_B^2}\left[\frac{\upsilon}{m}\mathbf{F}_\perp \pm \frac{\omega}{m}\mathbf{F}_\perp\times\hat{\mathbf{b}}\right]$$

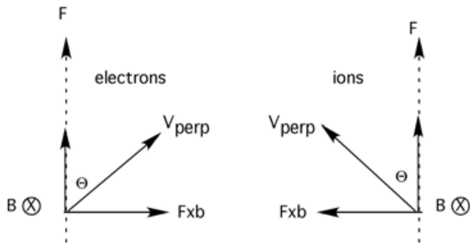
Principles of Ionospheric Dynamics

So perpendicular to the magnetic field we can write

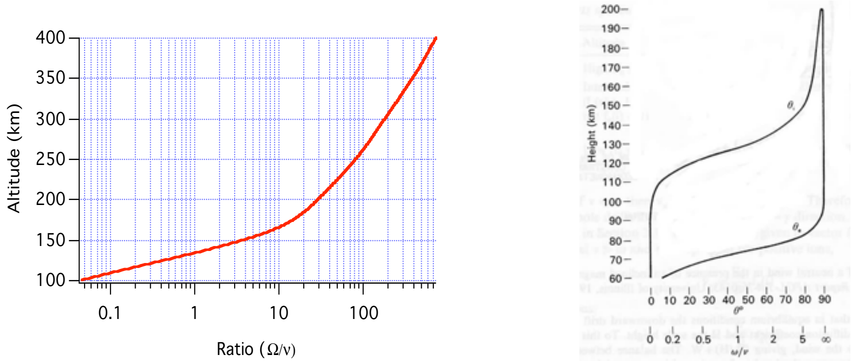
$$\mathbf{V}_\perp = \frac{\upsilon/m}{\upsilon^2+\omega_B^2}\left[\mathbf{F}_\perp + \frac{\omega_B}{\upsilon}\mathbf{F}_\perp\times\hat{\mathbf{b}}\right]$$

Illustrating that the charged particle moves in the direction of the force and perpendicular to the force.

Note that the ratio of the velocity parallel to the force to the velocity perpendicular to the force is $\frac{\upsilon}{\omega_B}$



Principles of Ionospheric Dynamics



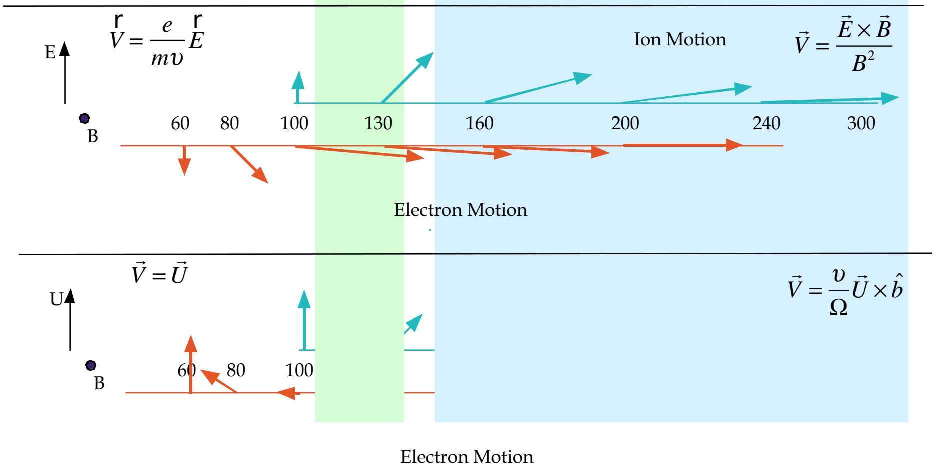
For electrons $\frac{\upsilon}{\omega_B}$ is very small through most of the ionosphere except below 80 km

For ions $\frac{\upsilon}{\omega_B}$ varies with altitude as shown. It is large below 130 km and small above 200 km

Principles of Ionospheric Dynamics

Charged particle Motions Perpendicular to B

$\Omega/\upsilon_{in} < 1 \quad \vec{V}_i^{\perp} \approx \vec{F}^{\perp}$ $\qquad \Omega/\upsilon_{in} > 1 \quad \vec{V}_i^{\perp} \approx \upsilon_{in}/\Omega\, \vec{F} \times \hat{b}$



Principles of Ionospheric Dynamics

Forces can produce different ion and electron velocities ….. Currents

If we express the force as an equivalent electric field, then we can express the current density in terms of the equivalent electric field. The matrix of coefficients is called the conductivity tensor.

Parallel to B $\mathbf{j}_{\parallel} = Ne\left(\mathbf{V}_{\parallel}^{i} - \mathbf{V}_{\parallel}^{e}\right)$

$$\mathbf{V}_{\parallel} = \frac{\omega_B}{\upsilon}\frac{1}{B}\mathbf{E}_{\parallel} = \frac{e}{m\upsilon}\mathbf{E}_{\parallel}$$

$$\mathbf{j}_{\parallel} = Ne^2\left(\frac{1}{m_i\upsilon_i} + \frac{1}{m_e\upsilon_e}\right)\mathbf{E}_{\parallel} \Rightarrow \sigma_0\mathbf{E}_{\parallel}$$

σ_0 is called the Direct Conductivity $\sigma_0 = Ne^2\left[\frac{1}{m_i\upsilon_i} + \frac{1}{m_e\upsilon_e}\right]$

Note that the electron collision frequency is dominated at high altitudes by ion-electron collisions and that this term is linearly proportional the charged particle number density. Thus the direct conductivity becomes constant at high latitudes.

Principles of Ionospheric Dynamics

Perpendicular to B we consider the current in the direction of the force and perpendicular to the force.

$$\mathbf{j}_{\perp} = \sigma_p\mathbf{E}_{\perp} - \sigma_h\mathbf{E}_{\perp} \times \hat{\mathbf{b}}$$

σ_p is called the Pedersen Conductivity σ_h is called the Hall Conductivity

$$\mathbf{V}_{\perp} = \frac{1}{\upsilon^2 + \omega_B^2}\left[\frac{\omega_B\upsilon}{eB}\mathbf{F}_{\perp} + \frac{\omega_B^2}{eB}\mathbf{F}_{\perp} \times \hat{\mathbf{b}}\right] \qquad \mathbf{V}_{\perp} = \frac{1}{\upsilon^2 + \omega_B^2}\left[\frac{\upsilon}{m}\mathbf{F}_{\perp} \pm \frac{\omega}{m}\mathbf{F}_{\perp} \times \hat{\mathbf{b}}\right]$$

$$\mathbf{J}_{\perp} = \frac{Ne}{\upsilon_i^{2`} + \omega_B^2}\left[\frac{\upsilon_i}{m_i}e\mathbf{E}_{\perp} + \frac{\omega_B}{m_i}e\mathbf{E}_{\perp} \times \hat{\mathbf{b}}\right] - \frac{Ne}{\upsilon_e^2 + \omega_B^2}\left[\frac{\upsilon_e}{m_e}(-e)\mathbf{E}_{\perp} - \frac{\omega_B}{m_e}(-e)\mathbf{E}_{\perp} \times \hat{\mathbf{b}}\right]$$

$$\mathbf{J}_{\perp} = Ne^2\left[\frac{\upsilon_i}{m_i\left(\upsilon_i^{2`} + \omega_B^2\right)} + \frac{\upsilon_e}{m_e\left(\upsilon_e^{2`} + \omega_B^2\right)}\right]\mathbf{E}_{\perp} + Ne^2\left[\frac{\omega_B}{m_i\left(\upsilon_i^{2`} + \omega_B^2\right)} - \frac{\omega_B}{m_e\left(\upsilon_e^{2`} + \omega_B^2\right)}\right]\mathbf{E}_{\perp} \times \hat{\mathbf{b}}$$

$$\sigma_p = \sigma_1 = Ne^2\left[\frac{\upsilon_i}{m_i\left(\upsilon_i^{2`} + \omega_B^2\right)} + \frac{\upsilon_e}{m_e\left(\upsilon_e^{2`} + \omega_B^2\right)}\right]$$

$$\sigma_h = \sigma_2 = Ne^2\left[\frac{\omega_B}{m_e\left(\upsilon_e^{2`} + \omega_B^2\right)} - \frac{\omega_B}{m_i\left(\upsilon_i^{2`} + \omega_B^2\right)}\right]$$

Collision Frequencies

$$\upsilon_i = \upsilon_{in} \approx 2.6 \times 10^{-9} N_n A^{-1/2}$$

$$A = \frac{m_i m_n}{m_i + m_n}$$

$$\upsilon_e = \upsilon_{en} + \upsilon_{ei}$$

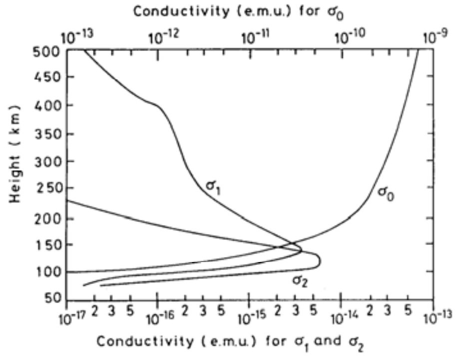
$$\upsilon_{en} \approx 5.4 \times 10^{-10} N_n T_e^{1/2}$$

$$\upsilon_{ei} \approx \left[34 + 4.18 \ln\left(T_e^3 \big/ N_e \right) \right] N_e T_e^{-3/2}$$

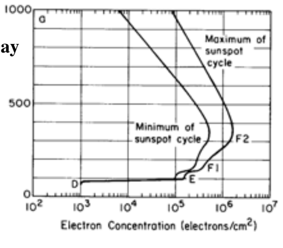
Number density in number per cubic centimeter

Mean mass in amu

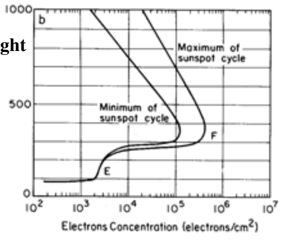
Ionospheric Conductivity



Day

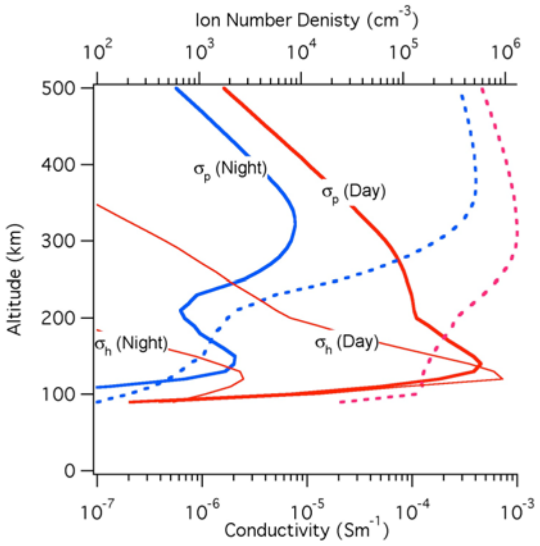


Night



- **Hall conductivity in a layer near 120 km**
  Essentially removed at night
- **Pedersen conductivity distributed in two regions**
  E-region greater than F-region during the daytime
  F region greater than E region at night.
- **Direct conductivity much greater than transverse conductivities everywhere above 90 km.**
  For spatial scales larger than 10 km magnetic field lines are almost electric equipotentials even though field-aligned currents flow (copper wire)

Ionospheric Conductivity



Current Continuity

Time scales for producing polarization electric fields is very short 10^{-6} s.

Charge difference required to produce polarization field is very small 1 in 10^8

$$\vec{J} = Ne\left(\vec{V}_i - \vec{V}_e\right) \qquad \nabla \bullet \mathrm{J}=0 \qquad \nabla_\perp \vec{J}^\perp + \frac{\partial \vec{J}^{\parallel}}{\partial \parallel} = 0$$

Consider separately
the current driven by the electric field
the current driven by other forces
[neutral winds(collisions with neutral particles) and gravity]

$$\int_{\substack{other\\end}}^{\substack{one\\end}} \nabla_\perp \vec{J}^\perp \, ds = \vec{J}^{\parallel \overset{one}{end}} - \vec{J}^{\parallel \overset{other}{end}} \qquad \int_{\substack{other\\end}}^{\substack{one\\end}} \nabla_\perp \vec{J}^\perp \Big|_{driver} ds + \int_{\substack{other\\end}}^{\substack{one\\end}} \nabla_\perp \left(\tilde{\sigma}_\perp \vec{\mathbf{E}}_\perp\right) ds = \vec{J}^{\parallel \overset{one}{end}} - \vec{J}^{\parallel \overset{other}{end}}$$

Express the electric field as the gradient of a scalar potential

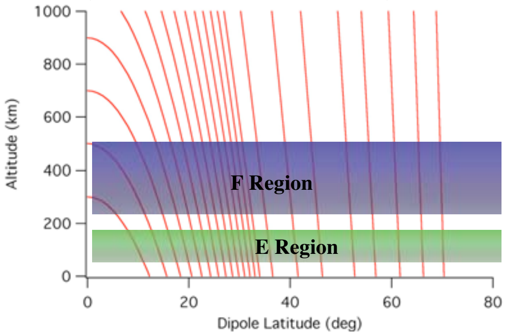
$$\boxed{\int_{\substack{other\\end}}^{\substack{one\\end}} \nabla_\perp \vec{J}^\perp \Big|_{driver} ds - \int_{\substack{other\\end}}^{\substack{one\\end}} \nabla_\perp \left(\tilde{\sigma}_\perp \nabla_\perp \Phi\right) ds = \vec{J}^{\parallel \overset{one}{end}} - \vec{J}^{\parallel \overset{other}{end}}}$$

This is the so-called "dynamo equation"

The Dynamo Equation at Low and Middle Latitudes

$$\int_{\substack{other\\ end}}^{\substack{one\\ end}} \nabla_\perp \vec{J}^\perp\Big|_{driver} ds - \int_{\substack{other\\ end}}^{\substack{one\\ end}} \nabla_\perp\left(\tilde{\sigma}_\perp \nabla_\perp \Phi\right) ds = \vec{J}^{\parallel \overset{one}{end}} - \vec{J}^{\parallel \overset{other}{end}}$$

Magnetic field terminates at the lower boundary at both ends.
No field-aligned current can flow at the ends
No contribution to the integrals above 1000 km
Electric Potential given by flux-tube integrated drivers and potential difference between flux tubes at high and low apex heights.



$$\int_{\substack{other\\ end}}^{\substack{one\\ end}} \nabla_\perp\left(\tilde{\sigma}_\perp \nabla_\perp \Phi\right) ds = \int_{\substack{other\\ end}}^{\substack{one\\ end}} \nabla_\perp \vec{J}^\perp\Big|_{driver} ds$$

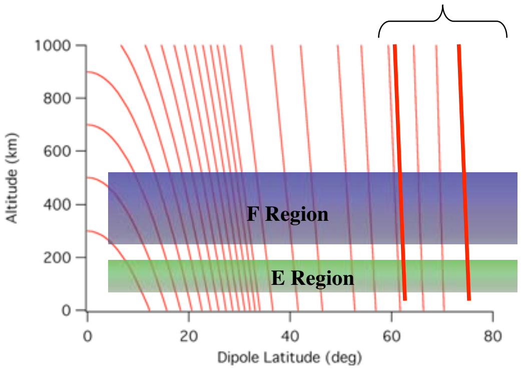
Dominant Driver is Neutral Wind. Thus...

$$\vec{J}^\perp\Big|_{driver} = \tilde{\sigma}\left(\vec{U} \times \vec{B}\right)$$

The Dynamo Equation at High Latitudes

$$\int_{\substack{other\\ end}}^{\substack{one\\ end}} \nabla_\perp \vec{J}^\perp\Big|_{driver} ds - \int_{\substack{other\\ end}}^{\substack{one\\ end}} \nabla_\perp\left(\tilde{\sigma}_\perp \nabla_\perp \Phi\right) ds = \vec{J}^{\parallel \overset{one}{end}} - \vec{J}^{\parallel \overset{other}{end}}$$

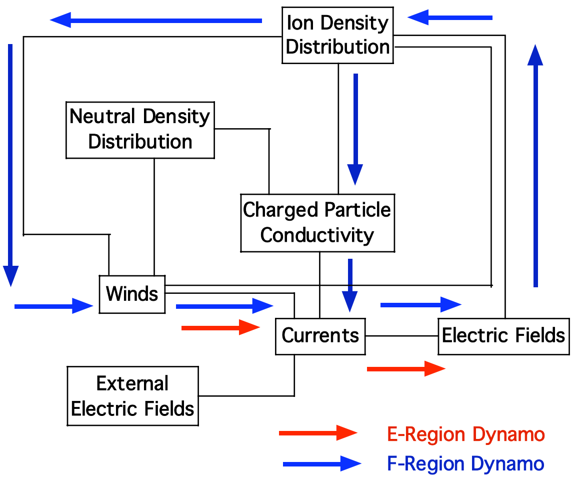
Magnetic field terminates at the lower boundary and upper boundary.
No field-aligned current can flow at lower boundary but is continuous with magnetosphere current at upper boundary
No contribution to the integrals above 1000 km
Internal drivers frequently neglected.



$$\int_{bottom}^{top} \nabla_\perp\left(\tilde{\sigma}_\perp \nabla_\perp \Phi\right) ds = -\vec{J}^{\parallel top}$$

Electric Potential given by field-aligned current and potential at lower boundary.

Electric Fields at Low and Middle Latitudes



Ion Density Distribution

Neutral Density Distribution

Charged Particle Conductivity

Winds

Currents

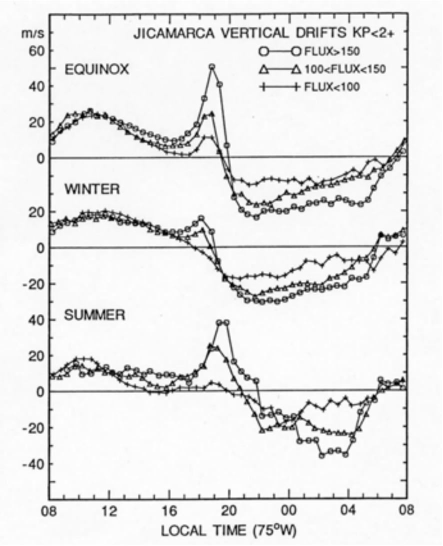
Electric Fields

External Electric Fields

E-Region Dynamo

F-Region Dynamo

Electric Fields at Low and Middle Latitudes
Vertical/Poleward-Equatorward Drifts



Fejer et al. JGR, 1993

At the equator and apex heights <600 km
drifts are dominated by diurnal component from wind driven current in the E region.

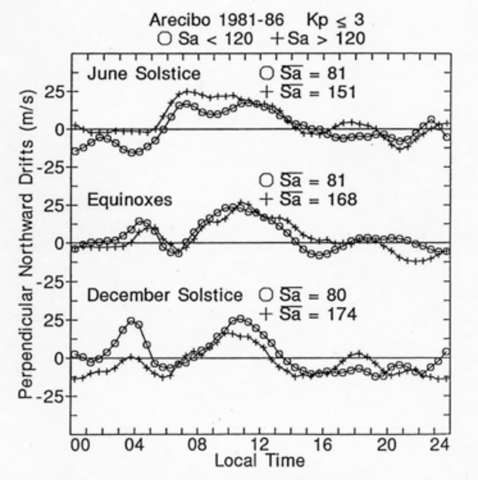
Up during the day
Down during the night

Average velocities or order 20 m/s

Quiet time departures produced by influence of F-region wind driven current.

24-hour average velocity approximately ZERO

Electric Fields at Low and Middle Latitudes
Vertical/Poleward-Equatorward Drifts



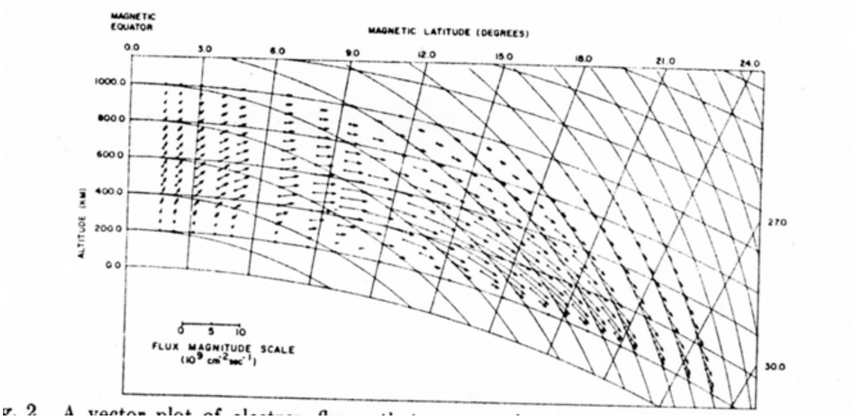
At higher apex heights/latitudes
drifts have diurnal and semi-diurnal components from wind driven current in the E region.

Average velocities or order 20 m/s

24-hour average velocity NOT zero.

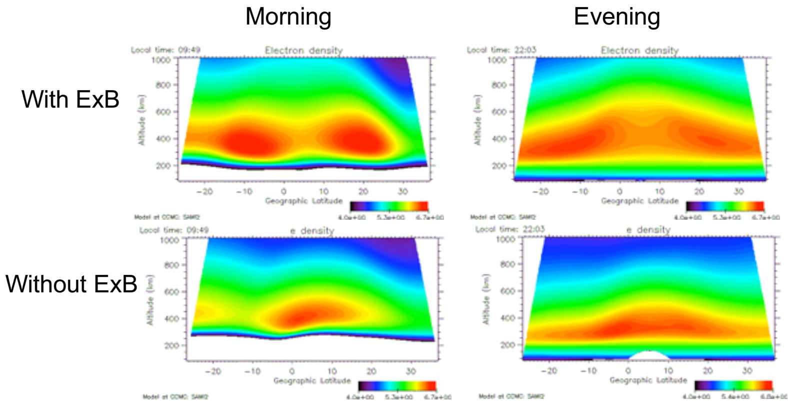
Fejer JGR, 1993

Electric Fields at Low and Middle Latitudes
Vertical/Poleward-Equatorward Drifts



Upward and downward drifts are accompanied by diffusive motions along the magnetic field.
Upward and poleward drifts are associated with downward and poleward diffusion producing a so-called ***fountain effect***

Electric Fields at Low and Middle Latitudes
Vertical/Poleward-Equatorward Drifts



SAMI2 Runs (Huba et al)
Courtesy of CCMC

Fountain effect redistributes the plasma at low latitudes changing:
the layer thickness
the layer peak density and height
the latitude distribution (Appleton Anomaly)

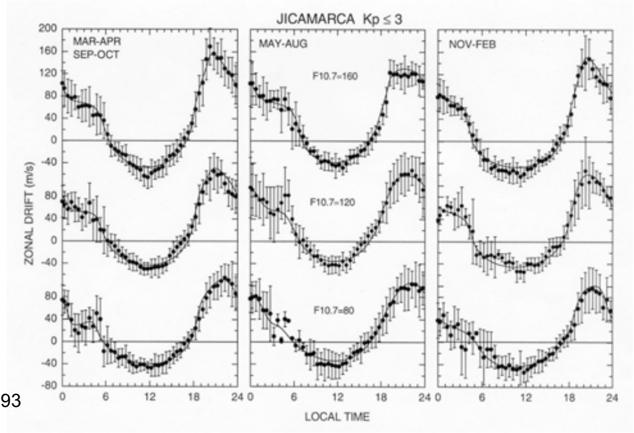
Anomaly is a sensitive function of the ExB drift *history*

Electric Fields at Low and Middle Latitudes
Vertical/Poleward-Equatorward Drifts

Effects of vertical drifts
Daytime
- Increase layer number density and layer thickness
  - Decrease plasma loss rate
  - Transport plasma to higher altitudes to be replaced by solar production

Nighttime
- Increase layer number density and layer height.
- Decrease drag on neutral atmosphere
  - Transport plasma to higher altitudes decreases the loss rate and decreases the plasma number density at lower altitudes.
- Increase effectiveness of gravity dynamo discussed later.

Electric Fields at Low and Middle Latitudes
Zonal/East-West Drifts



Fejer et al., 1993

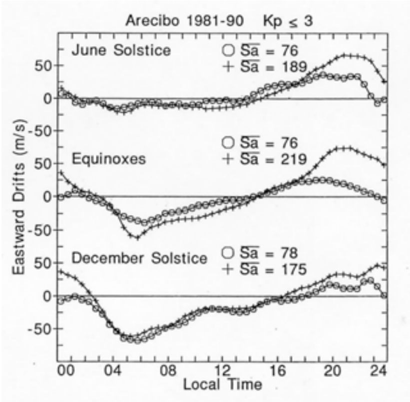
At the equator

Zonal Ion Drifts have strong diurnal variation - west during the day and east at night.

Nighttime eastward drifts are larger than daytime westward drifts.

24-hour average drift is eastward. The ionosphere super-rotates.

Electric Fields at Low and Middle Latitudes
Zonal/East-West Drifts



Fejer, 1993

At middle latitudes

Zonal Ion Drifts have weaker diurnal variation - west during the day and east at night.

Nighttime eastward drifts are larger than daytime westward drifts.

24-hour average drift is sometimes eastward and sometimes westward dependent on season and solar activity.

Ionosphere approximately corotates

Electric Fields at Low and Middle Latitudes
Zonal/East-West Drifts

Effects of east-west drifts

Change in the effective length of daylight and darkness

Westward drifts over a 12 hour period means that the plasma stays in sunlight for periods longer than 12 hours

Eastward drifts over a 12 period mean that the plasma stays in darkness for periods shorter than 12 hours

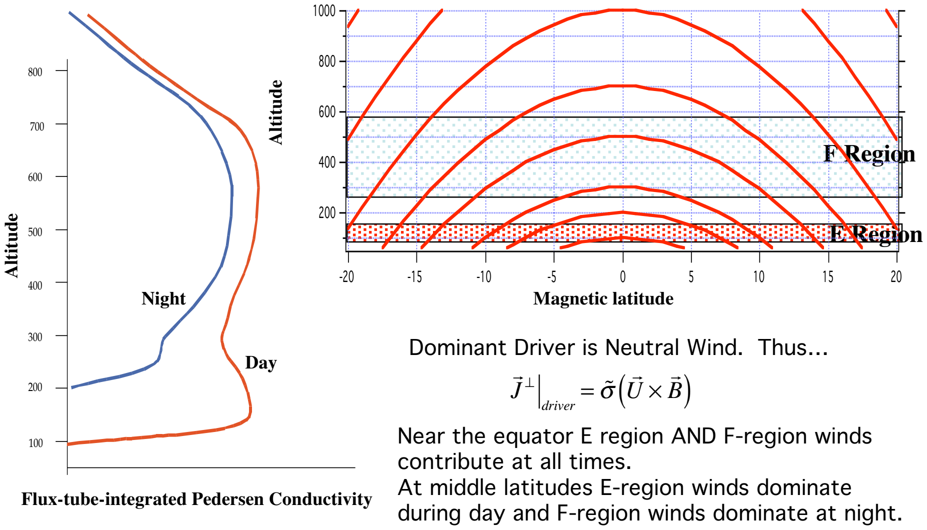
The plasmasphere has a differential rotation rate

At the equator for radial distances less that about 7320 km (1000 km altitude) the plasma superrotates.

At radial distance of 7320 - 10000 km (1000-3500 km altitude) the plasma approximately corotates.

At radial distances between 10000 - 25000 (3500 - 19000 km altitude) the plasma subrotates.

Electric Fields at Low and Middle Latitudes
Electric field depends on flux-tube integrated drivers and conductivity.



Dominant Driver is Neutral Wind. Thus...

$$\vec{J}^{\perp}\Big|_{driver} = \tilde{\sigma}\left(\vec{U}\times\vec{B}\right)$$

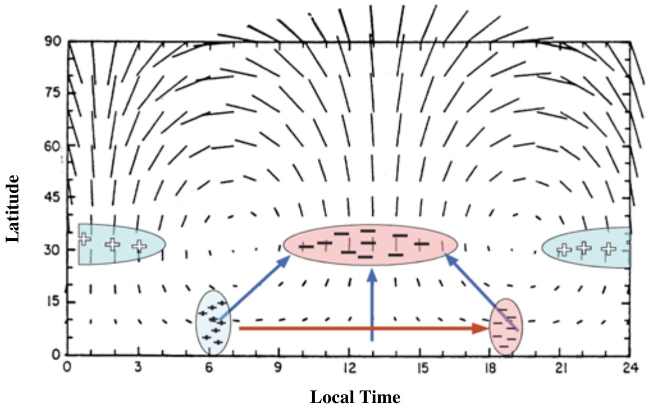
Near the equator E region AND F-region winds contribute at all times.
At middle latitudes E-region winds dominate during day and F-region winds dominate at night.

E-Region Dynamo

Electric fields produced by gradients in the driving current

$$\vec{J}^{\perp}\Big|_{driver} = \tilde{\sigma}\left(\vec{U}\times\vec{B}\right) = \sigma_p\left(\vec{U}\times\vec{B}\right) + \sigma_h \vec{U}B$$

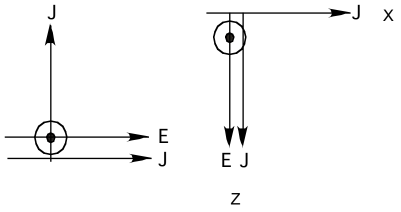
Neutral wind blows toward the pole during the daytime with return flow at night.
Conductivity is high at day and low at night
Conductivity decreases with increasing latitude



The Equatorial Electrojet

It is convenient to consider the E region as a layer where the Hall and Pedersen conductivities are important and where the layer only allows horizontal currents to flow.

Near the equator an east-west electric field (neutral wind) will drive a vertical current that cannot close anywhere and therefore must be suppressed by a vertical polarization electric field.



$$J_x = \sigma_p E_x + \sigma_h E_z$$

$$J_z = -\sigma_h E_x + \sigma_p E_z$$

$$J_z = 0 \Rightarrow \sigma_h E_x = \sigma_p E_z \Rightarrow J_x = \sigma_p E_x + \sigma_h \frac{\sigma_h}{\sigma_p} E_x$$

$$J_x = \sigma_3 E_x \qquad \sigma_3 = \sigma_p + \frac{\sigma_h^2}{\sigma_p}$$

This enhanced Pedersen conductivity is called the Cowling conductivity and results from making the vertical current zero.

The resulting enhancement in the east west current at the equator is called the ***equatorial electrojet.***

E-region Layer Conductivities

With the assumption that the vertical current is suppressed in the layer it is possible to write the horizontal current in terms of the north-south (y) and east-west (x) components of the electric field. The e-field can easily include a UxB wind driver.

$$J_x = \sigma_{xx} E_x + \sigma_{xy} E_y$$
$$J_y = \sigma_{yy} E_y - \sigma_{xy} E_x$$

The so called layer conductivities can be expressed as

$$\sigma_{xx} = \frac{\sigma_0 \sigma_1}{\left(\sigma_1 \cos^2 I + \sigma_0 \sin^2 I\right)}$$

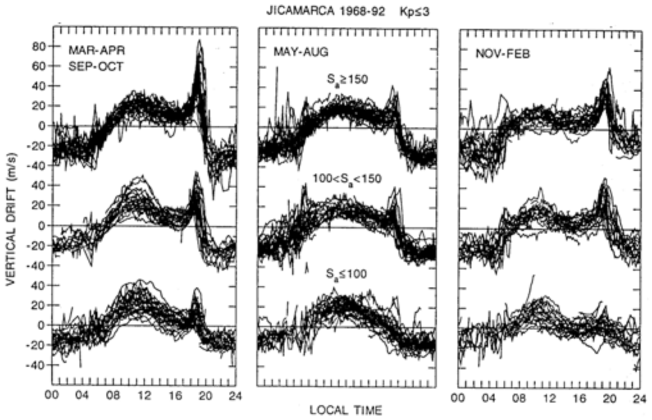
$$\sigma_{yy} = \frac{\sigma_0 \sigma_1 \sin^2 I + \left(\sigma_1{}^2 + \sigma_2{}^2\right) \cos^2 I}{\left(\sigma_1 \cos^2 I + \sigma_0 \sin^2 I\right)}$$

$$\sigma_{xy} = \frac{\sigma_0 \sigma_2 \sin I}{\left(\sigma_1 \cos^2 I + \sigma_0 \sin^2 I\right)}$$

Note that these layer conductivities reduce to just the direct and cowling conductivity at the equator.

Observed ExB Drifts

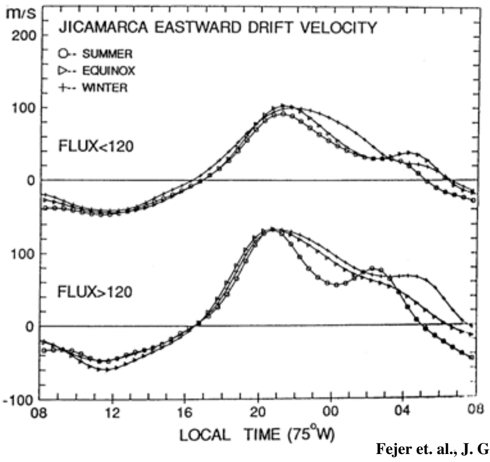
- **Mapped to the F-region zonal field produces vertical drifts up during day and down at night.**
- **Pre-reversal enhancement in vertical drift is not explained by E-region dynamo.**



Scherliess and Fejer, J. Geophys. Res., *104*, 6829, 1999

Observed ExB Drifts

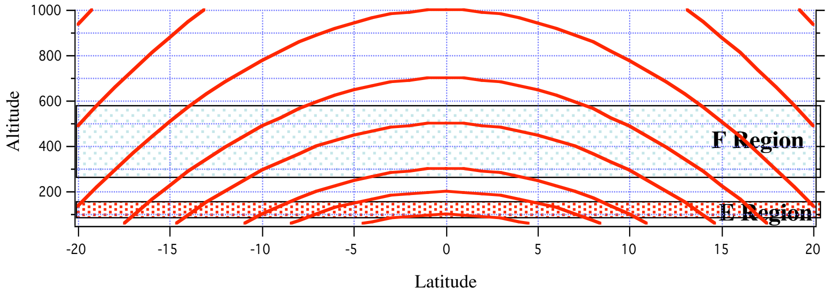
- **Mapped to the F-region, meridional field produces zonal drifts westward during day and eastward at night.**
- **Day/Night asymmetry in amplitude of zonal drifts is not explained by E-region dynamo.**



Fejer et. al., J. Geophys. Res., *96*, 13,901, 1991

F-Region Dynamo

$$\vec{J}^{\perp}\Big|_{driver} = \tilde{\sigma}\left(\vec{U}\times\vec{B}\right) = \sigma_p\left(\vec{U}\times\vec{B}\right)$$



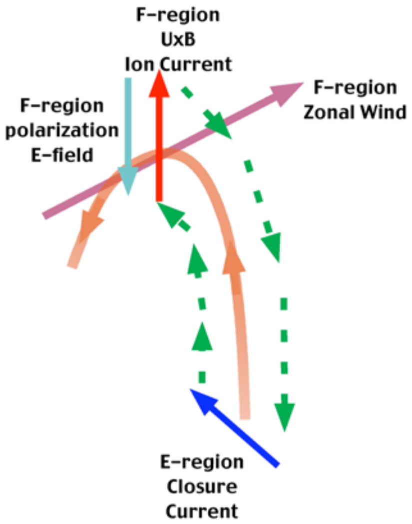
Winds drive ions along B and in direction UxB.

Zonal Winds drive ions perpendicular to B up and down.

Meridional winds
  Drive a small current compared to zonal winds since field lines are almost horizontal.
  Cause asymmetries in ion distribution along B affecting flux tube integrated conductivity.

F-Region Dynamo

$$\vec{J}^{\perp}\Big|_{driver} = \tilde{\sigma}\left(\vec{U}\times\vec{B}\right) = \sigma_p\left(\vec{U}\times\vec{B}\right)$$

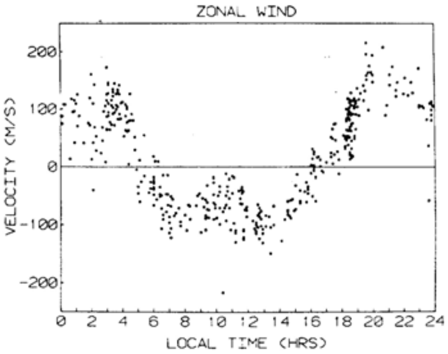


- Winds drive ions in direction UxB.
- Divergence in wind driven current in topside and bottomside of flux-tube integrated F-region.
- Polarization fields to make current flowing through E region and F region equal.

$$\Sigma_p^{\,E} E = \Sigma_p^{\,F} UB - \Sigma_p^{\,F} E$$

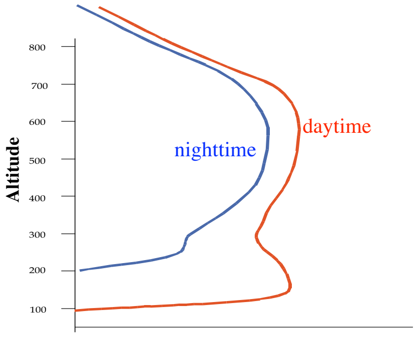
$$E_p = \frac{\Sigma_p^{\,F} UB}{\Sigma_p^{\,F} + \Sigma_p^{\,E}}$$

F-Region Winds and Currents



Wharton et al., Geophys. Res. Lett, *11*, 531, 1984

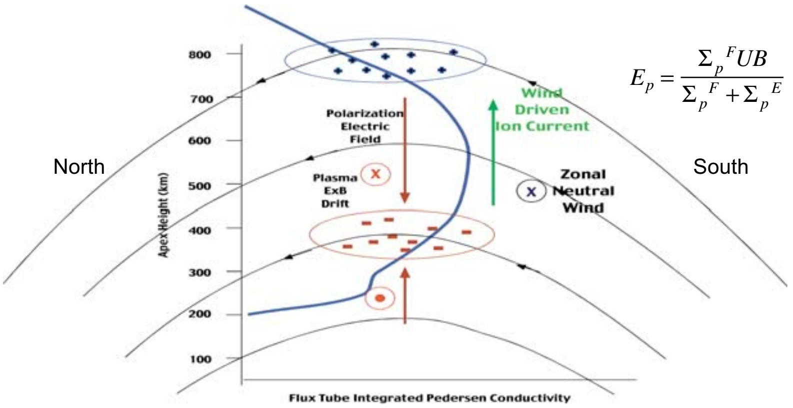
- **Meridional winds have small component perpendicular to B and are neglected compared to zonal winds.**
- **Zonal winds above 250 km essentially constant with altitude.**



Flux-tube-integrated Pedersen conductivity

- **Zonal winds drive ions perpendicular to magnetic field --up and down.**

F-Region Dynamo

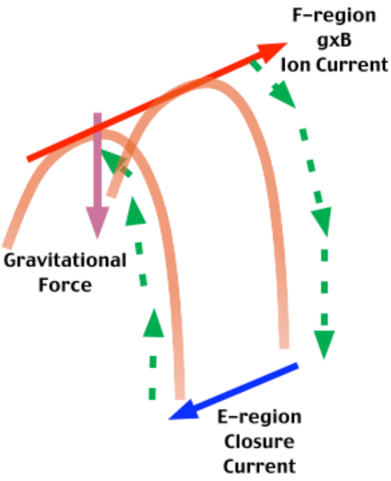


$$E_p = \frac{\Sigma_p{}^F UB}{\Sigma_p{}^F + \Sigma_p{}^E}$$

Bottomside F-region polarization field drives ions eastward above the bottomside (asymmetry in east-west drifts) and westward below it. (so-called evening vortex)

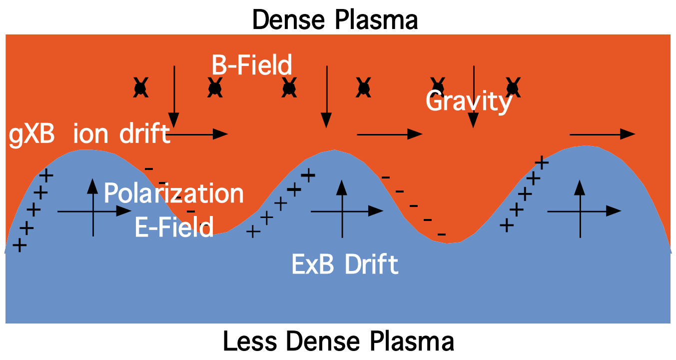
Bottomside F-region polarization charges produce pre-sunset eastward field. (so-called pre-reversal enhancement)

Gravity Dynamo



- **Gravitational force produces eastward drift of ions in F-region.**
- **Gravity driven current has divergences where gradients in the flux tube integrated conductivity exist.**
- **Polarization charges accumulate at night when E-region prevents current closure.**

Gravitational Rayleigh-Taylor Instablity



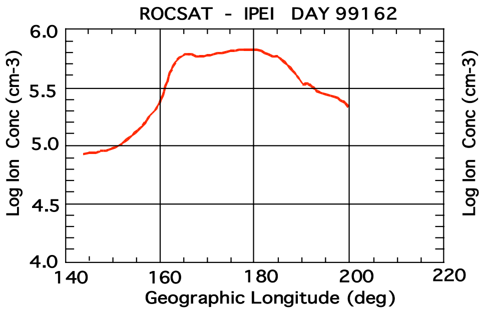
Flux tubes with low conductivity (low density) drift upwards.

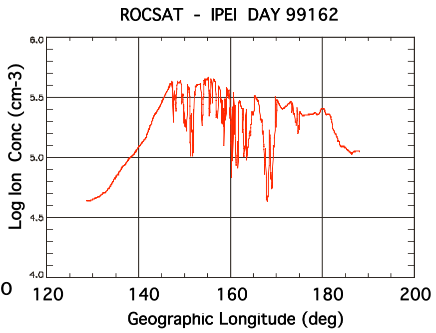
Depleted flux tubes appear in F-region called spread-F

Note: zonal current can also be produced by zonal electric field.

Spread-F Depletion Drifts

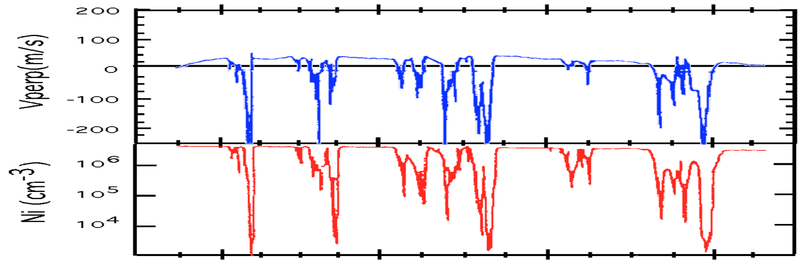
Appearance of Plasma Irregularities





This instability turns a normally smooth F-region ion density distribution into a highly structured plasma environment

Spread-F Depletion Drifts



UT (hr:mn:sc)	05:58:00	06:00:00	06:02:00	06:04:00
Alt (km)	314	313	313	312
Bx/B	0.26	0.30	0.34	0.38
MLT (hr)	20.9	21.4	21.9	22.4
DipLat (deg)	-17.2	-15.5	-13.5	-11.2
Shell Ht (km)	952.3	826.8	698.3	572.6
SZA (km)	132.4	140.3	148.2	156.0

Hanson and Bambgboye, J. Geophys. Res., *89*, 8997, 1984.

Depletions in the ion density in the F-region create gradients in the current driven by electric fields, gravity and neutral winds.

$$E_z^{depl} = \frac{\Sigma_p^{back}}{\Sigma_p^{depl}} E_z^{back} + \frac{\Sigma_{h,i}^{back} - \Sigma_{h,i}^{depl}}{\Sigma_p^{depl}} \frac{mg}{q}$$

Depletion drifts are not a local phenomenon.

Plasma Motions Parallel to B

Force Parallel to B

$$\mathbf{F}_{\|} - m\upsilon \mathbf{V}_{\|} = 0$$

$$\mathbf{V}_{\|} = \frac{\omega_B}{\upsilon} \frac{1}{eB} \mathbf{F}_{\|}$$

Large neutral winds are always horizontal so if U denotes the wind in the magnetic meridian then the component along the magnetic field is $U \cos I$

This velocity will move the plasma along the magnetic field line in latitude and also move it vertically up and down.

For a neutral wind $\mathbf{F} = m\upsilon \mathbf{U}$ $\mathbf{V}_{\|} = U_{\|} = U \cos I$

If the magnetic field has an inclination I then the vertical ion velocity is

$$\mathbf{V}_z = U \cos I \sin I = \frac{1}{2} U \sin 2I$$

A neutral wind is most effective in lifting the charged particles when the inclination is 45 deg

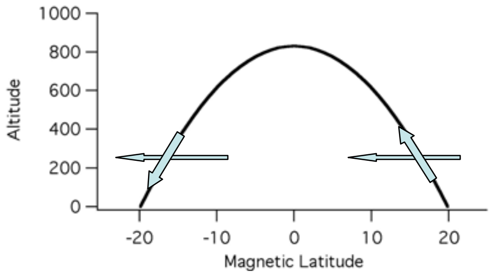
If the force is applied by an electric field then $\mathbf{F} = e\mathbf{E}$

$$\mathbf{F}_{\|} - m\upsilon \mathbf{V}_{\|} = 0$$

$$\mathbf{V}_{\|} = \frac{\omega_B}{\upsilon} \frac{1}{B} \mathbf{E}_{\|}$$

Electric fields parallel to the magnetic field are rare in the ionosphere except where the collision frequency is very large. We will not discuss them further.

Plasma Motions Parallel to B

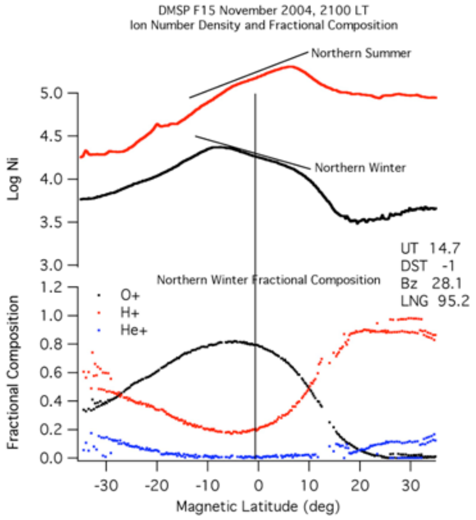


F-region meridional winds blow from summer to winter.

In the summer the layer is raised and the plasma loss rate is lowered

In the winter the layer is lowered and the plasma loss rate is raised

Plasma Motions Parallel to B



Meridional winds in summer and winter produce characteristic latitude gradients in the ion number density.

Above the peak F region density the composition also changes at night.

Enhanced loss rates in the F region during the winter night allow H+ to diffuse downward along the magnetic field.