THE IONOSPHERE/PLASMASPHERE SYSTEM: A TUTORIAL

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THE IONOSPHERE

- weakly ionized plasma surrounding the earth

- neutrals ionized by sun’s EUV radiation (10Å- 1000Å)
- 90 km to 1000 km or so
- weakly ionized: $n_e \lesssim 10^6 \text{ cm}^{-3}$; $n_n \lesssim 10^{10} \text{ cm}^{-3}$
- multi-ion plasma
- very low $\beta$ plasma: $\beta \sim 10^{-5}$
- $T \lesssim 3000K$ (or .3 eV)
- collisional
- anisotropic conductivities: $\sigma_\parallel \gg \sigma_\perp$
- assume magnetic field lines are equipotentials
IONOSPHERE

ions/electrons vs altitude

![Graph showing density of different ions and electrons vs altitude in the ionosphere. The graph includes curves for $O^+$, $H^+$, $NO^+$, $O_2^+$, and electrons (e) at various altitudes. The graph is divided into two regions: E region and F region.](image)
IONOSPHERE

electrons: latitude vs altitude (Appleton anomaly)
equatorial $E \times B$ drift: upward during day - downward at night
TEC

\[ TEC = \int n_e \, dz \]

where \( dz \) is along line of sight between satellite and ground-based receiver (usually convert to vertical)

- 1 TECU = \( 10^{16} \) m\(^{-2}\)
- typical values 10’s – low 100’s
THE PLASMASPHERE overview

- IMAGE data: He$^+$ (Goldstein ...)
- high density ($> 10^2$ cm$^{-3}$)
  - cold ($T \approx$ few 1000K) plasma
- ions: H$^+$ ($> 90\%$) and He$^+$
  (and a little O$^+$)
- range $2 < L < 7$
- collisionless
- storm-time erosion: hrs
- refilling: days
PLASMASPHERE
electron density (Berube et al., JGR, 2005)

\[ \log_{10} n_e = -0.66L + 4.89 \]
ions: $H^+, O^+, He^+, N^+, N_2^+, NO^+, O_2^+$
interhemispheric model
vertical and zonal $E \times B$ drift
neutral species: NRLMSISE00/HWM93
parallelized using MPI
nonorthogonal, nonuniform fixed grid
global coverage ($\pm 88^\circ$)
solve continuity, velocity, temperature equations
include ion inertia along $B$
volland/stern, weimer, and RCM potential
ion continuity

\[ \frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \mathbf{V}_i) = P_i - L_i n_i \]

ion velocity

\[ \frac{\partial \mathbf{V}_i}{\partial t} + \mathbf{V}_i \cdot \nabla \mathbf{V}_i = -\frac{1}{\rho_i} \nabla P_i + \frac{e}{m_i} \mathbf{E} + \frac{e}{m_i c} \mathbf{V}_i \times \mathbf{B} + \mathbf{g} \]

\[ -\nu_{in} (\mathbf{V}_i - \mathbf{V}_n) - \sum_j \nu_{ij} (\mathbf{V}_i - \mathbf{V}_j) \]

ion temperature

\[ \frac{\partial T_i}{\partial t} + \mathbf{V}_i \cdot \nabla T_i + \frac{2}{3} T_i \nabla \cdot \mathbf{V}_i + \frac{2}{3} \frac{1}{n_i k} \nabla \cdot \mathbf{Q}_i = Q_{in} + Q_{ij} + Q_{ie} \]
• electron momentum

\[ 0 = -\frac{1}{n_em_e} b_s \frac{\partial P_e}{\partial s} - \frac{e}{m_e} E_s \]

• electron temperature

\[ \frac{\partial T_e}{\partial t} - \frac{2}{3} \frac{1}{n_e k} b_s^2 \kappa_e \frac{\partial T_e}{\partial s} \frac{\partial T_e}{\partial s} = Q_{en} + Q_{ei} + Q_{phe} \]
\[ \nabla \cdot \Sigma \nabla \Phi = S(V_n, J_\parallel) \quad E = -\nabla \Phi \]

\[ \begin{align*}
\frac{\partial}{\partial p} p \Sigma_{pp} \frac{\partial \Phi}{\partial p} &+ \frac{\partial}{\partial \phi} \Sigma_{p\phi} \frac{\partial \Phi}{\partial \phi} \\
- \frac{\partial}{\partial p} \Sigma_H \frac{\partial \Phi}{\partial \phi} &+ \frac{\partial}{\partial \phi} \Sigma_H \frac{\partial \Phi}{\partial p}
\end{align*} \]

Pedersen

Hall

\[ \begin{align*}
= \frac{\partial F_p V}{\partial p} + \frac{\partial F_\phi V}{\partial \phi} \\
+ f(J_\parallel)
\end{align*} \]

neutral wind

high latitude currents
\[ \nabla \cdot \Sigma \nabla \Phi = S(V_n, J_\parallel) \]

- penetration electric field
  - \( S(V_n, J_\parallel(t)) \)
  - time scale: mins

- stormtime dynamo electric field
  - \( S(V_n(t), J_\parallel) \)
  - time scale: hrs
PENETRATION ELECTRIC FIELD

SAMI3/RCM: quiet time vs stormtime

\[ \nabla \cdot \Sigma \nabla \Phi = S( V_n, J_{\parallel} ) \]

SAMI3

HWM

RCM
PENETRATION ELECTRIC FIELD
stormtime impact on ionosphere (Mannucci et al., GRL, 2005)
DISTURBANCE WINDS

TIME-GCM (courtesy G. Crowley)

QUIET DAY

STORM DAY
PLASMASPHERE DYNAMICS
stormtime response (Grebowsky, JGR, 1970)
- corotation potential

\[ \Phi_{\text{cor}} = -\frac{92}{r} \text{(kV)} \]

- volland/stern/maynard/chen potential \((K_p = 6)\)

\[ \Phi_{\text{vsmc}} = Ar^2 \sin(\phi) \quad A = \frac{P(t)}{(1 - 0.159K_p + 0.0093K_p^2)^3} \text{(kV)} \]
H$^+$/He$^+$ CONTOURS
hydrogen / helium ion density contours at $t = 52$ hrs and 96 hrs in equatorial plane
$H^+ / He^+$ ISOSURFACES

electron density isosurfaces at $t = 52$ hrs and 96 hrs in equatorial plane
H⁺/He⁺ PROFILES

line plots of hydrogen and helium ion density vs $L$ shell
Electron Number Density (cm$^{-3}$)

Log$_{10} n_e = -0.66L + 4.89$
ELECTRON DENSITY AND SAMI3 DATA

\[ \log_{10} n_e = -0.66L + 4.89 \]
Electron Density and SAMI3 Data

$\log_{10} n_e = -0.66L + 4.89$
**PLASMASPHERE REFILLING**

**back-of-the envelope calculation**

- area $\simeq 10^{15} \text{ cm}^2$
- volume $\simeq 3 \times 10^{25} \text{ cm}^3$
- flux $\simeq 4 \times 10^7 \text{ cm}^{-2} \text{ s}^{-1}$
- refill rate = area $\times$ flux $= 8 \times 10^{22} \text{ s}^{-1}$
- time to refill flux tube $= n_{avg} \times$ volume / rate
- for $n_{avg} \sim 10^3 \text{ cm}^{-3}$
- refill time $\sim 104 \text{ hrs}$
  $\sim 4 \text{ days}$
PLASMASPHERE REFILLING

consistent with Krall et al., ANGEO, 2008
FEB 2001 STORM

refilling: solar wind data → Weimer model

SAMI3 REFILLING
use Weimer model (Krall and Huba, GRL, 2013; Krall et al., JGR, in press, 2014)

\[
dn_e/dt = 3.81(6.8/L)^{4.94}\text{cm}^{-3}\text{day}^{-1}
\]  

(1)
IONOSPHERE/PLASMASPHERE SIGNATURES


Equatorial Projection

GPS TEC [10,150] TECu 19:30 UT March 31, 2001

IMAGE EUV Plasmapause

19:30 UT TEC > 50 TECu
SAMI3/RCM

march 29, 2001 storm

Electron Density (cm$^{-3}$)

DAY 090  UT 08:15

TEC

0.0e+00  7.5e+01  1.5e+02
march 29, 2001 storm - impact on TEC and electron density profile

(a) TEC

(b) Electron density profile at different times:
- 08:45 UT (top)
- 07:15 UT (middle)
- 05:45 UT (bottom)
quiet time: plasmasphere just an extension of ionosphere (reasonably well-modeled by SAMI3/Weimer)

stormtime: high latitude dynamics become important
- penetration electric field
- disturbance dynamo electric field

effects
- erosion of plasmasphere/plume development
- stormtime enhanced density (SED) in mid- to high-latitude ionosphere

some fundamental stormtime dynamics confirmed using SAMI3/RCM: relationship of SED and plume