THE IONOSPHERE/PLASMASPHERE SYSTEM: A TUTORIAL

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2014 GEM Workshop
Portsmouth, VA
16 June 2014

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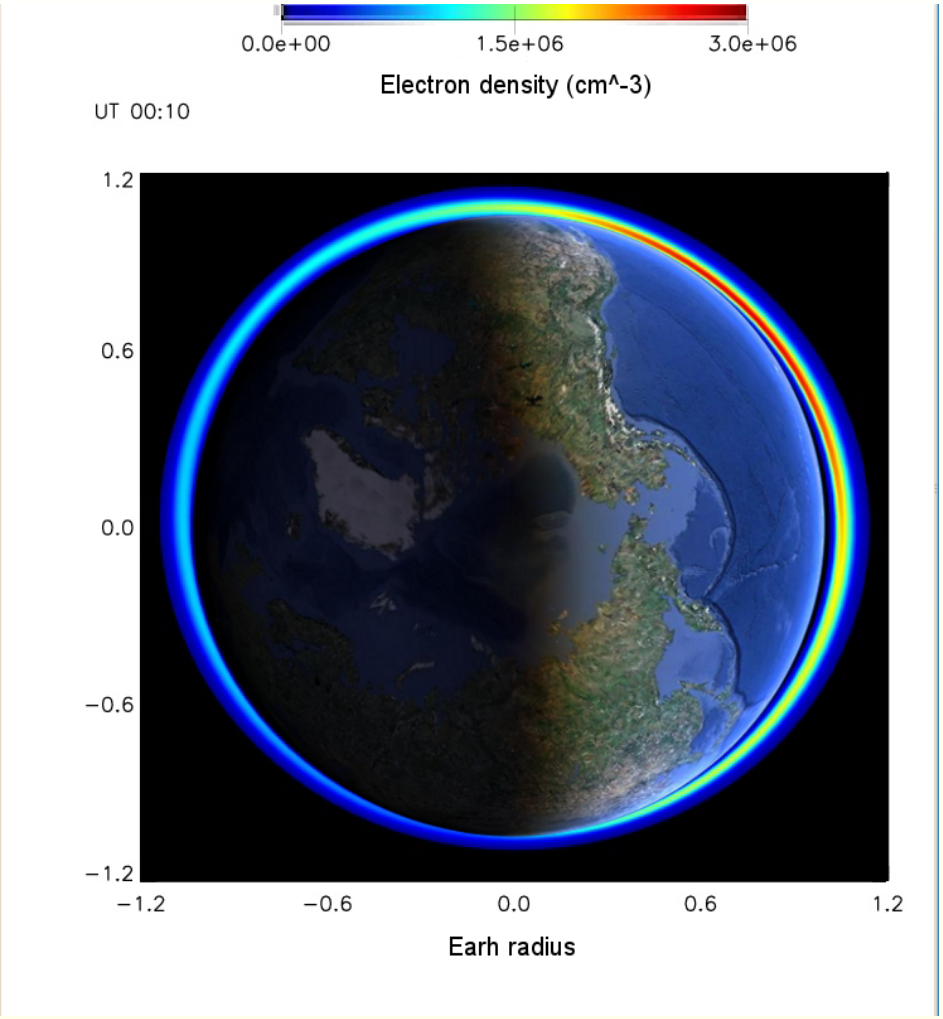
supported by NRL Base Funds and NASA LWS grants

THE IONOSPHERE

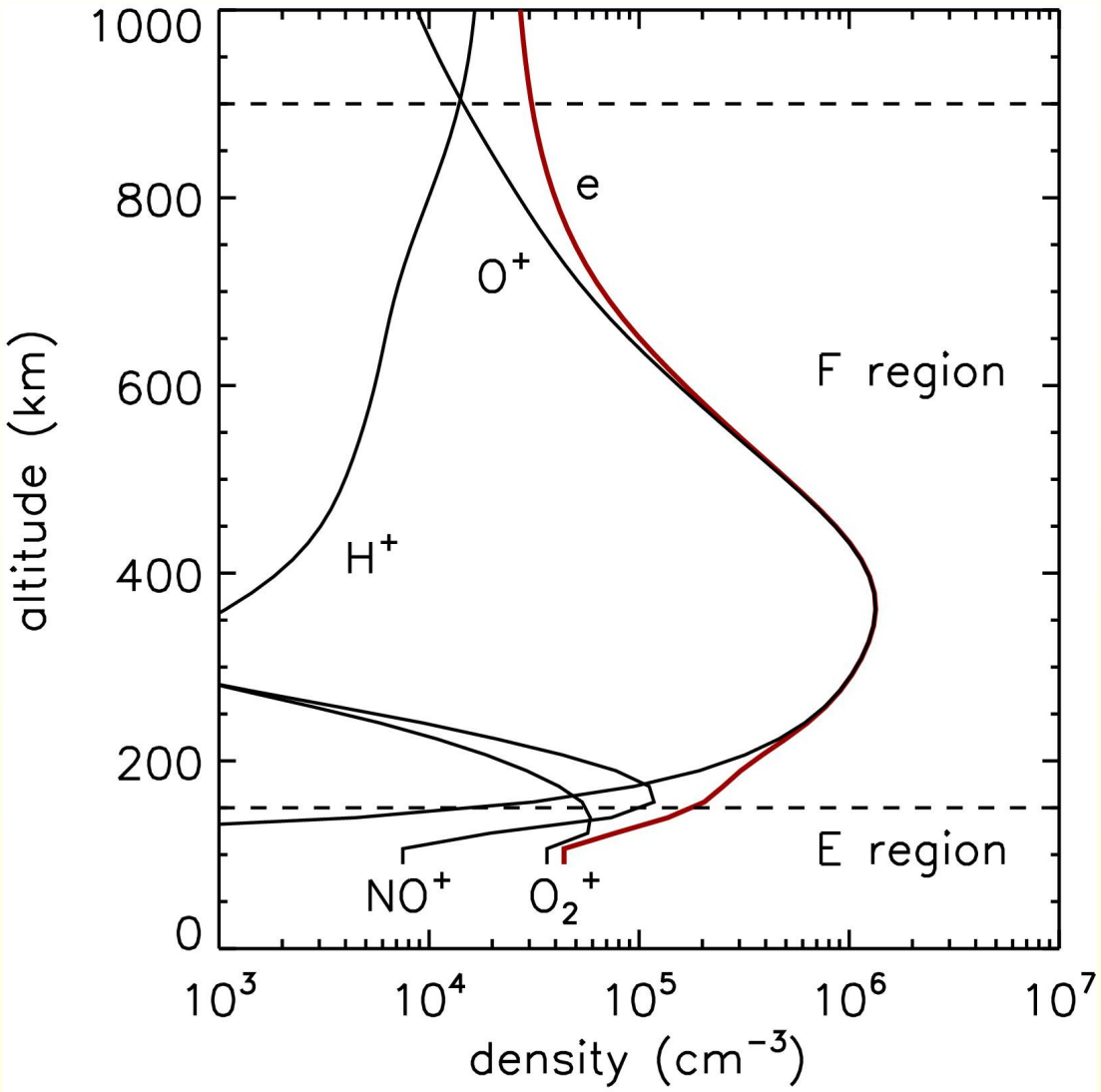
weakly ionized plasma surrounding the earth

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



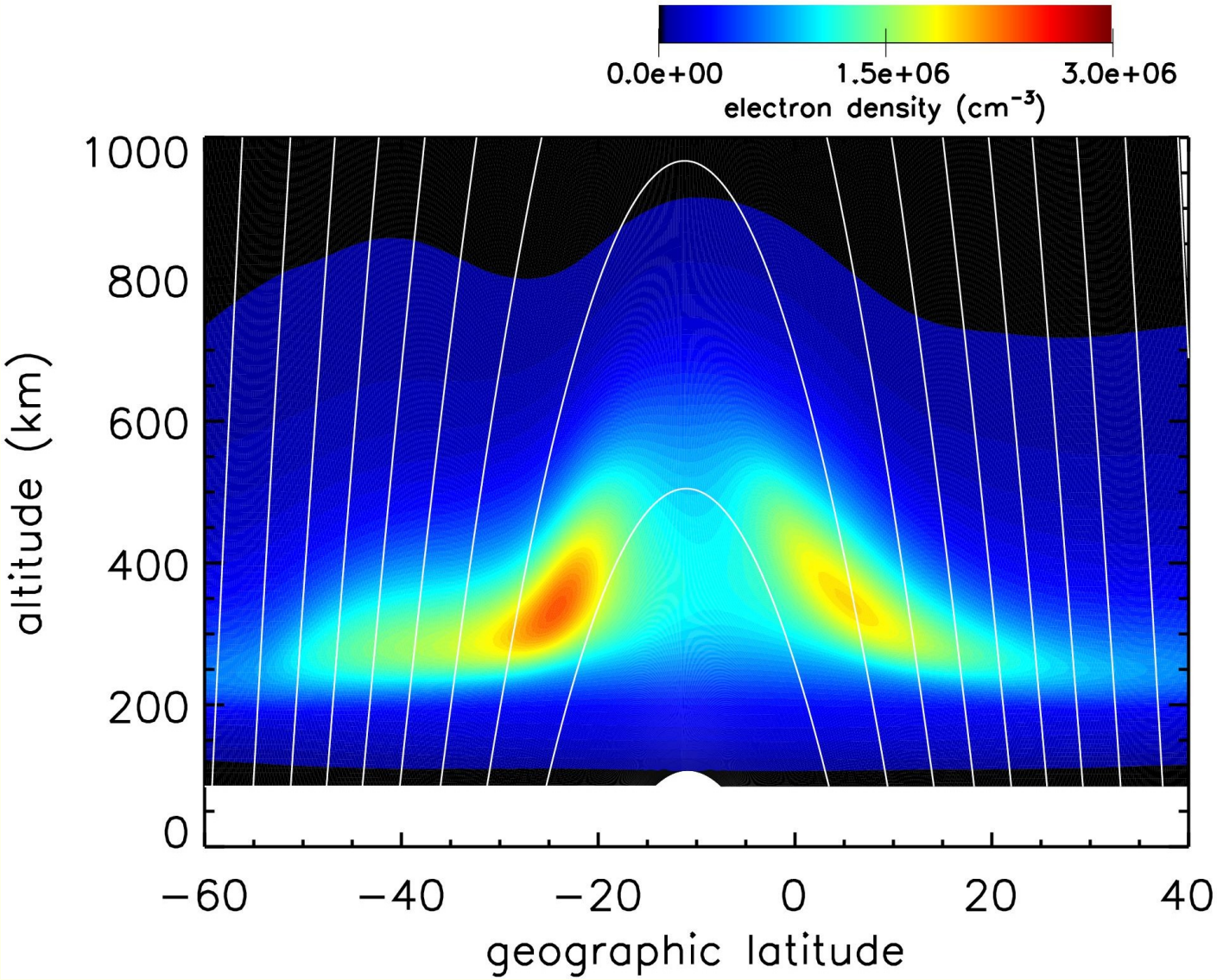
IONOSPHERE

ions/electrons vs altitude



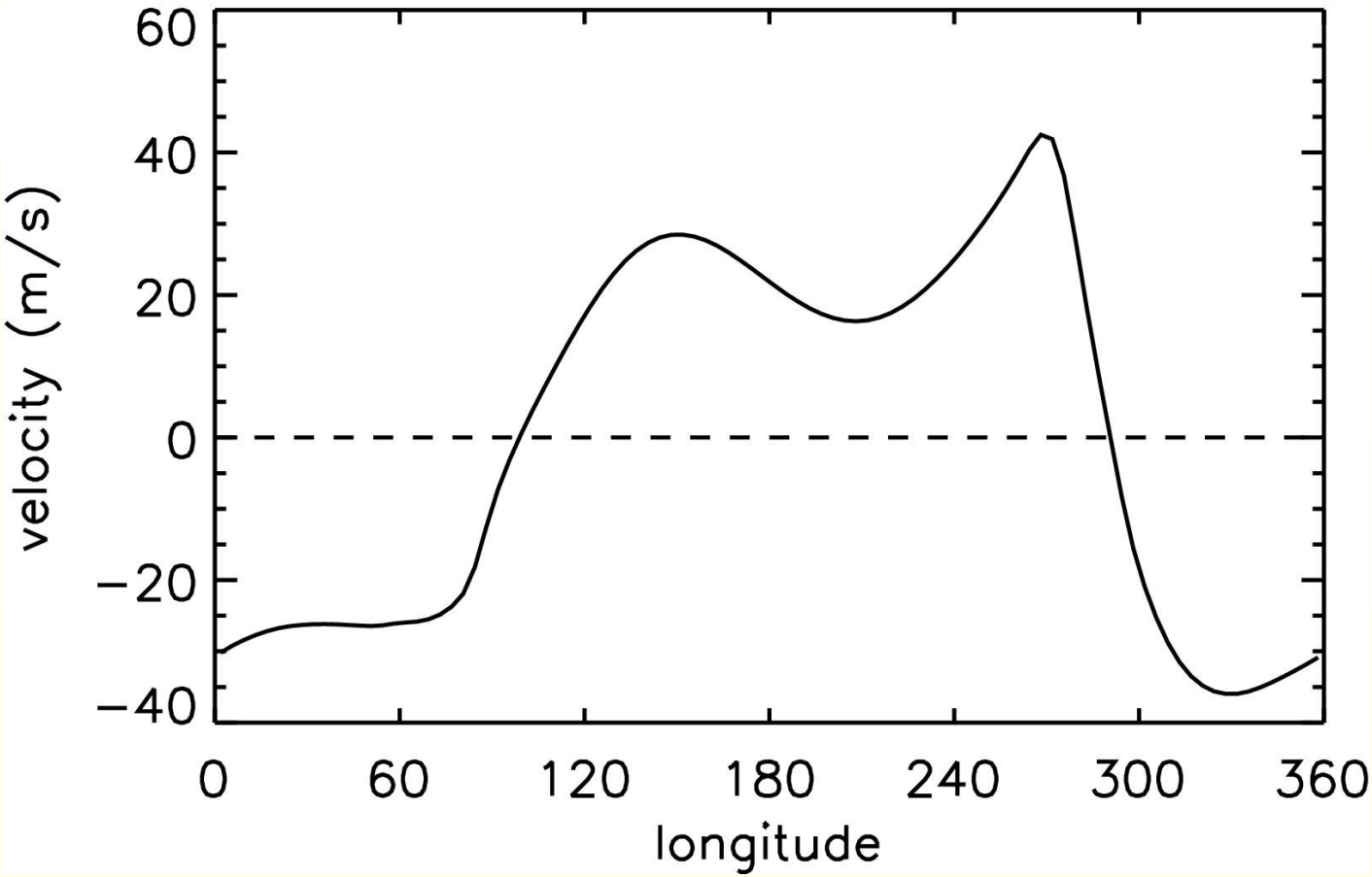
IONOSPHERE

electrons: latitude vs altitude (Appleton anomaly)



IONOSPHERE

equatorial $E \times B$ drift: upward during day - downward at night



IONOSPHERE

total electron content: measure of ionosphere 'strength'

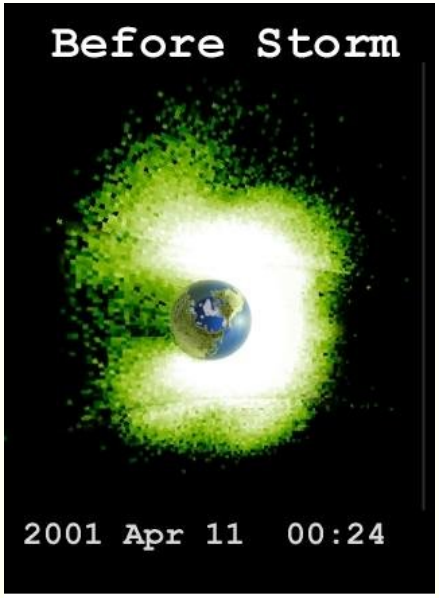
- TEC

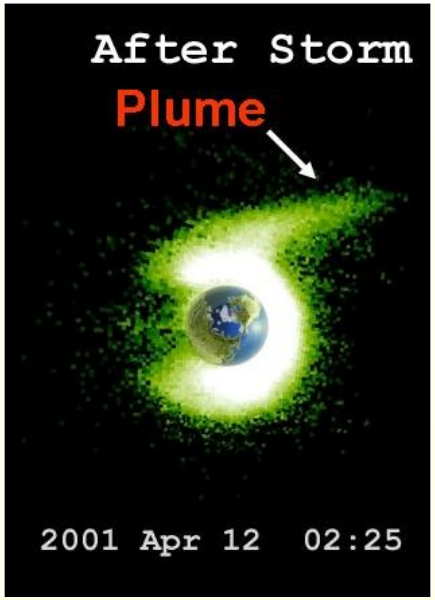
$$TEC = \int n_e \, dz$$

  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

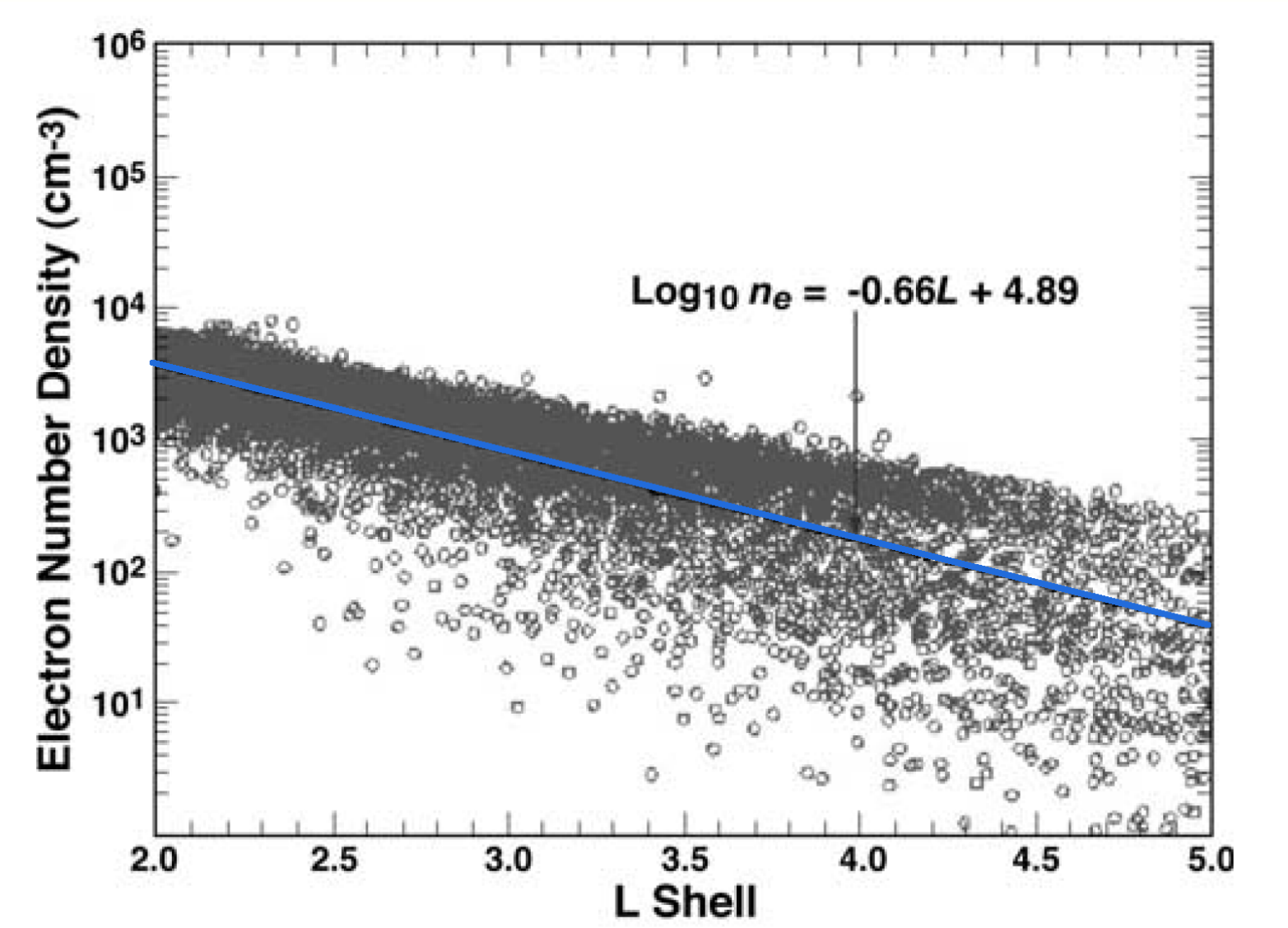
- IMAGE data: He^+ (Goldstein ...)
- high density ($> 10^2$ cm^{-3})
  cold (T $\simeq$ few 1000K) plasma
- ions: H^+ ($> 90\%$) and He^+
  (and a little O^+)
- range $2 < L < 7$
- collisionless
- storm-time erosion: hrs
- refilling: days





PLASMASPHERE

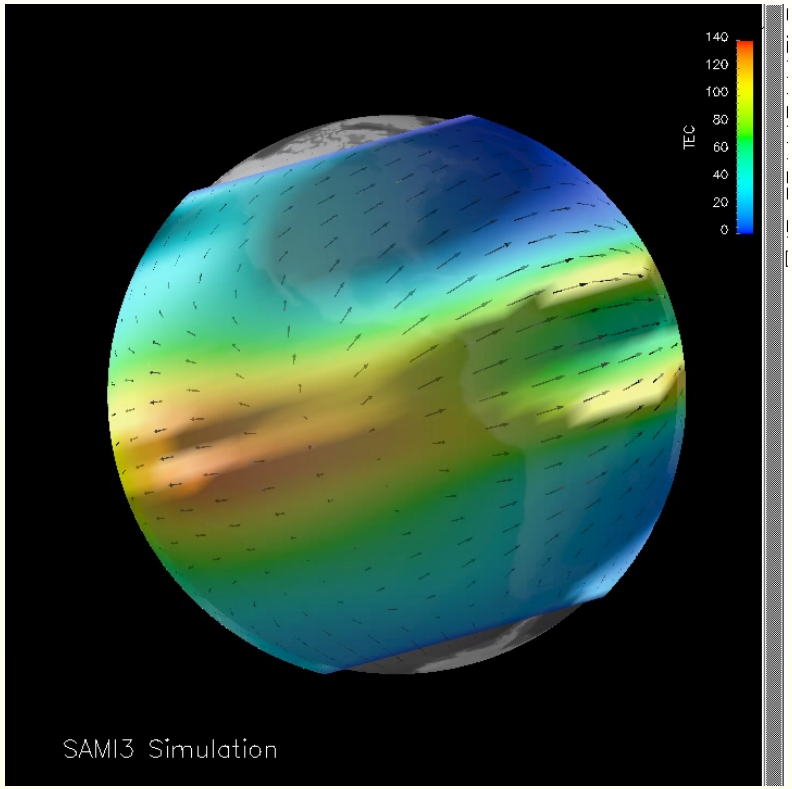
electron density (Berube et al., JGR, 2005)



SAMI3

NRL comprehensive ionosphere/plasmasphere model

- 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 ($\pm 88°$)
- solve continuity, velocity, temperature equations
- include ion inertia along $\mathbf{B}$
- volland/stern, weimer, and RCM potential



MODELING THE PLASMA DYNAMICS

- ion continuity

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

- ion velocity

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

$$-\nu_{in}(\mathbf{V}_i - \mathbf{V_n}) - \sum_j \nu_{ij} \left(\mathbf{V}_i - \mathbf{V}_j\right)$$

- ion temperature

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

MODELING THE PLASMA DYNAMICS

- electron momentum

$$0 = -\frac{1}{n_e m_e} b_s \frac{\partial P_e}{\partial s} - \frac{e}{m_e} E_s$$

- electron temperature

$$\frac{\partial T_e}{\partial t} - \frac{2}{3}\frac{1}{n_e k} b_s^2 \frac{\partial}{\partial s} \kappa_e \frac{\partial T_e}{\partial s} = Q_{en} + Q_{ei} + Q_{phe}$$

THE POTENTIAL EQUATION

2D based on $\nabla \cdot \mathbf{J} = 0$

$$\nabla \cdot \Sigma \nabla \Phi = S(V_n, J_{\|}) \qquad \mathbf{E} = -\nabla \Phi$$

$$\underbrace{\frac{\partial}{\partial p} p \Sigma_{pp} \frac{\partial \Phi}{\partial p} + \frac{\partial}{\partial \phi} \frac{\Sigma_{p\phi}}{p} \frac{\partial \Phi}{\partial \phi}}_{\text{Pedersen}} \quad \underbrace{-\frac{\partial}{\partial p} \Sigma_H \frac{\partial \Phi}{\partial \phi} + \frac{\partial}{\partial \phi} \Sigma_H \frac{\partial \Phi}{\partial p}}_{\text{Hall}}$$

$$= \underbrace{\frac{\partial F_{pV}}{\partial p} + \frac{\partial F_{\phi V}}{\partial \phi}}_{\text{neutral wind}} \quad \underbrace{+ f(J_{\|})}_{\text{high latitude currents}}$$

THE POTENTIAL EQUATION

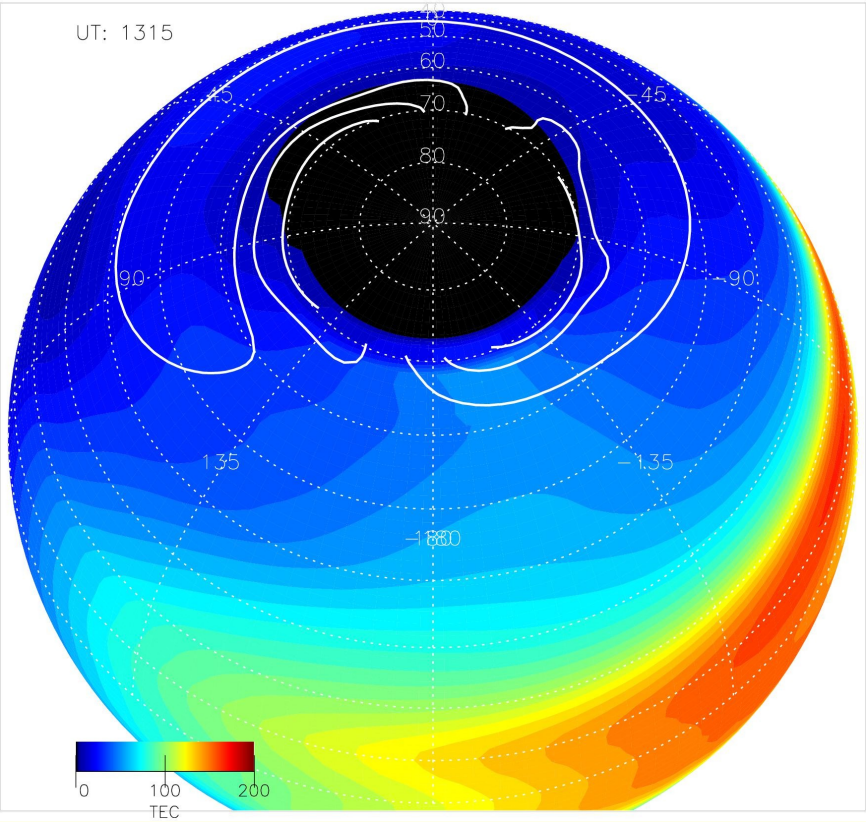
primary influence of storm-time dynamics on the ionosphere/plasmasphere system

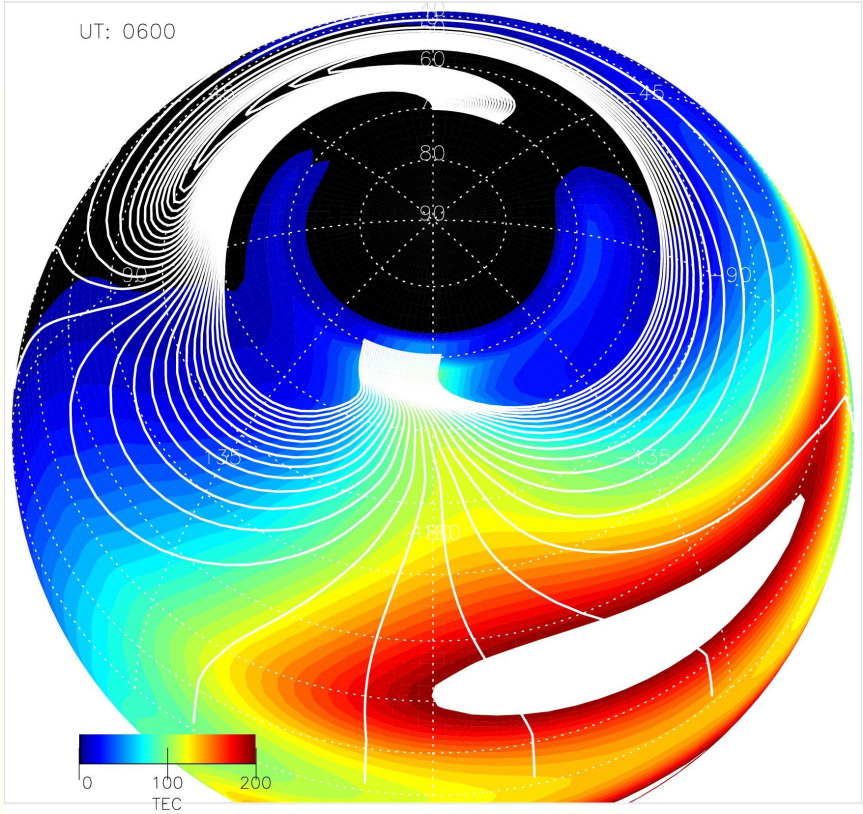
$$\nabla \cdot \Sigma \nabla \Phi = S(V_n, J_{\parallel})$$

- 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

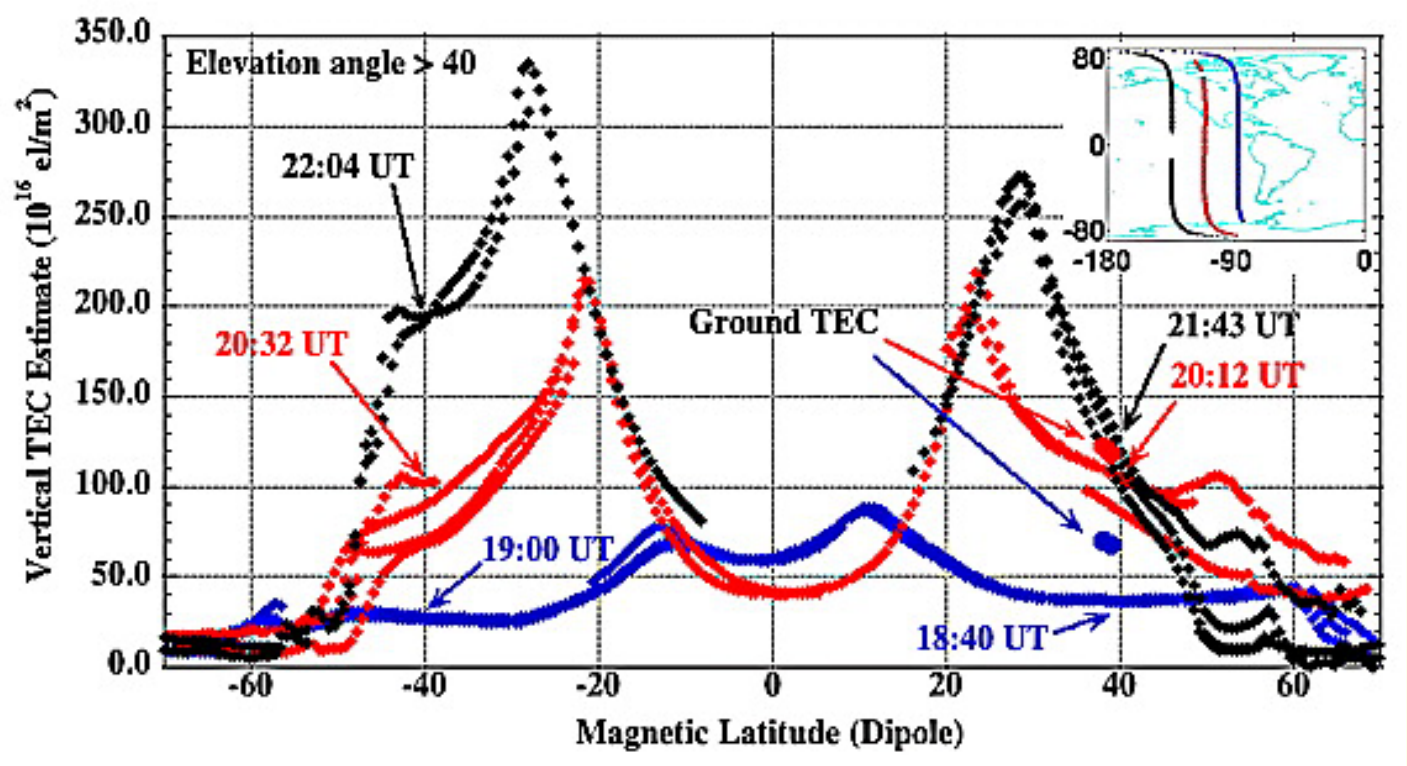




$$\nabla \cdot \underbrace{\Sigma}_{\text{SAMI3}} \nabla \Phi = S(\underbrace{V_n}_{\text{HWM}}, \underbrace{J_{\parallel}}_{\text{RCM}})$$

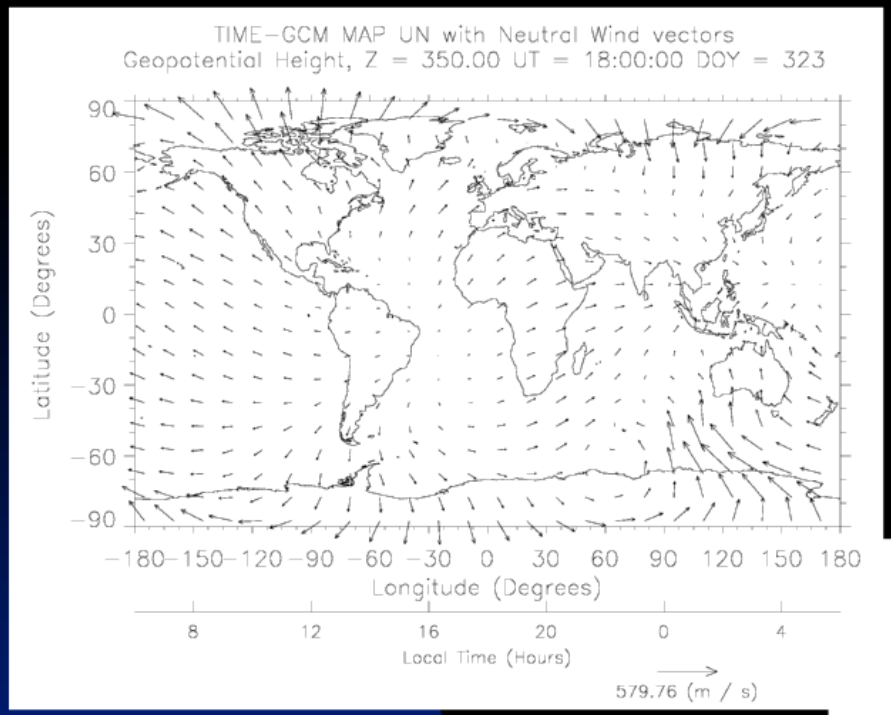
PENETRATION ELECTRIC FIELD

stormtime impact on ionosphere (Mannucci et al., GRL, 2005)



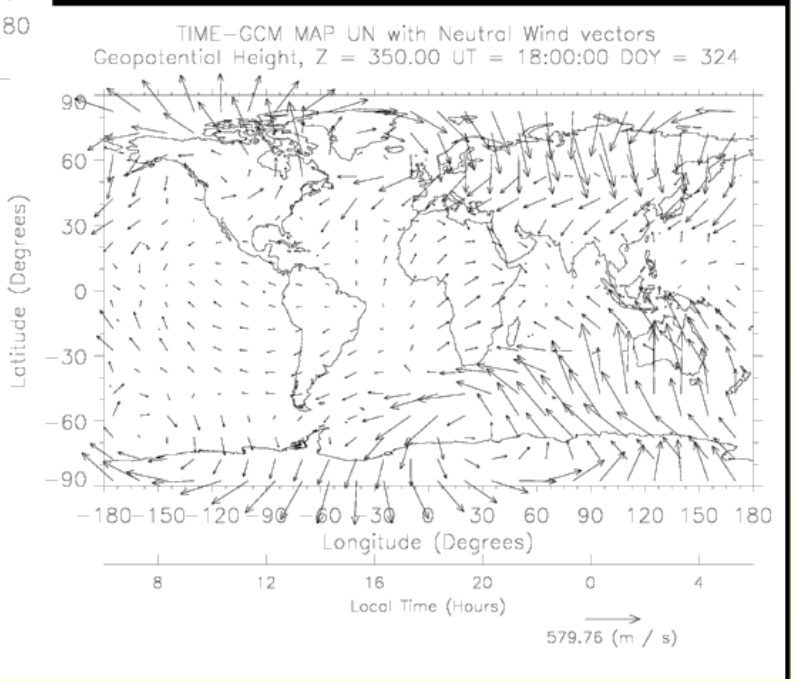
DISTURBANCE WINDS

TIMEGCM (courtesy G. Crowley)



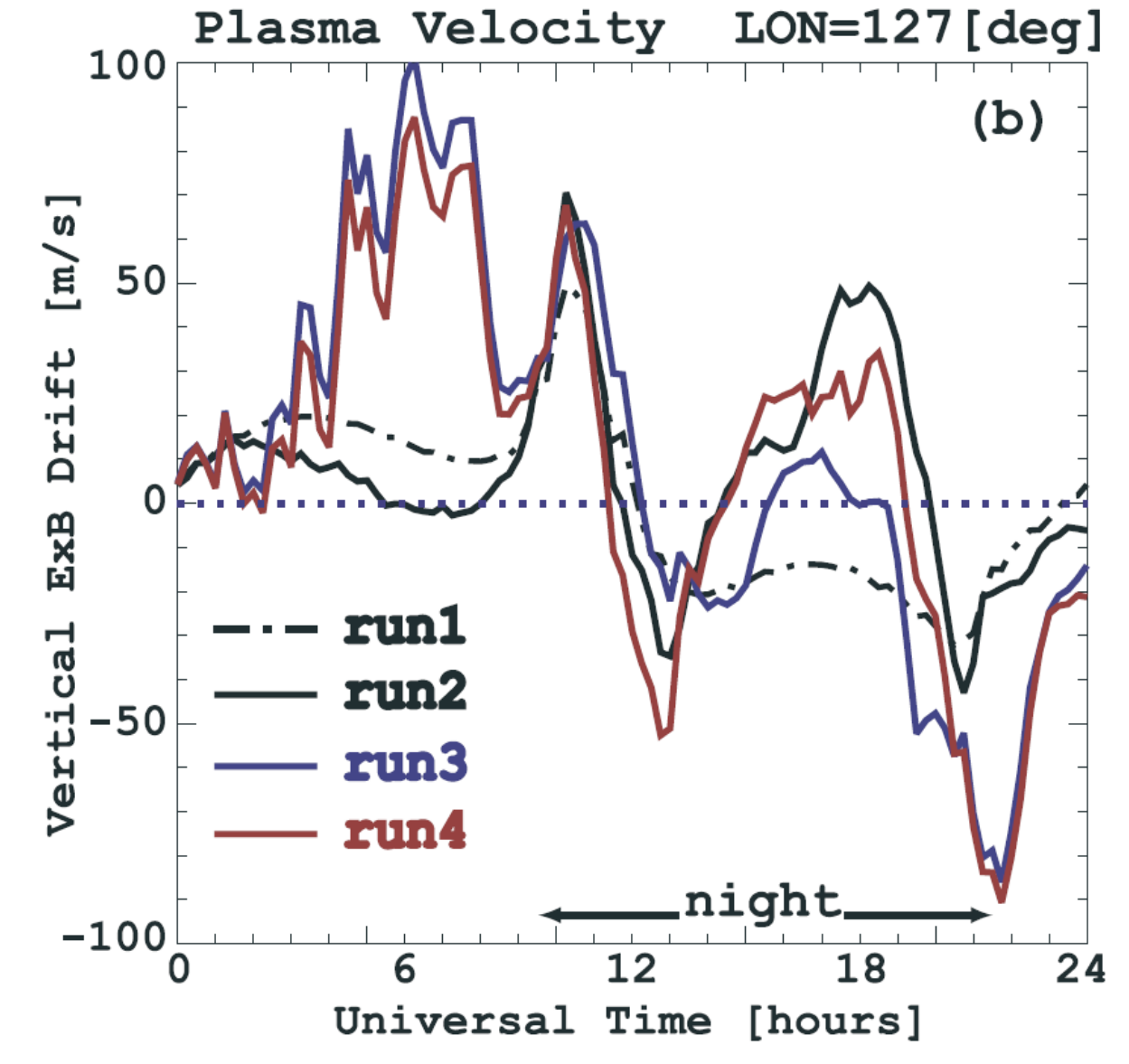
QUIET DAY

STORM DAY



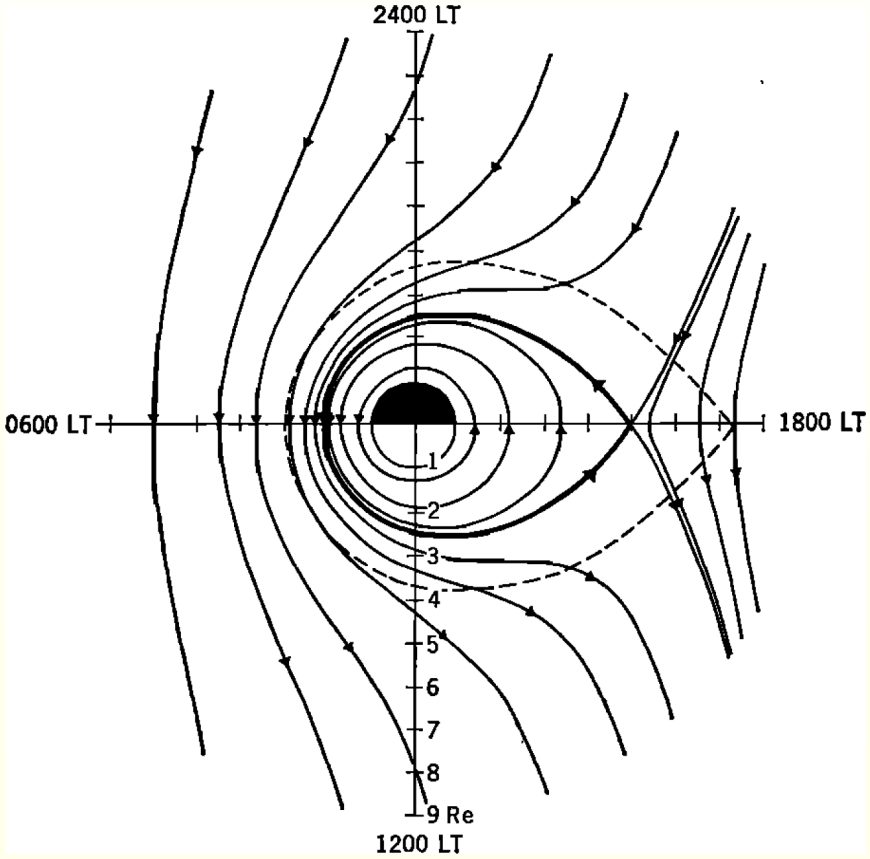
DISTURBANCE DRIFTS

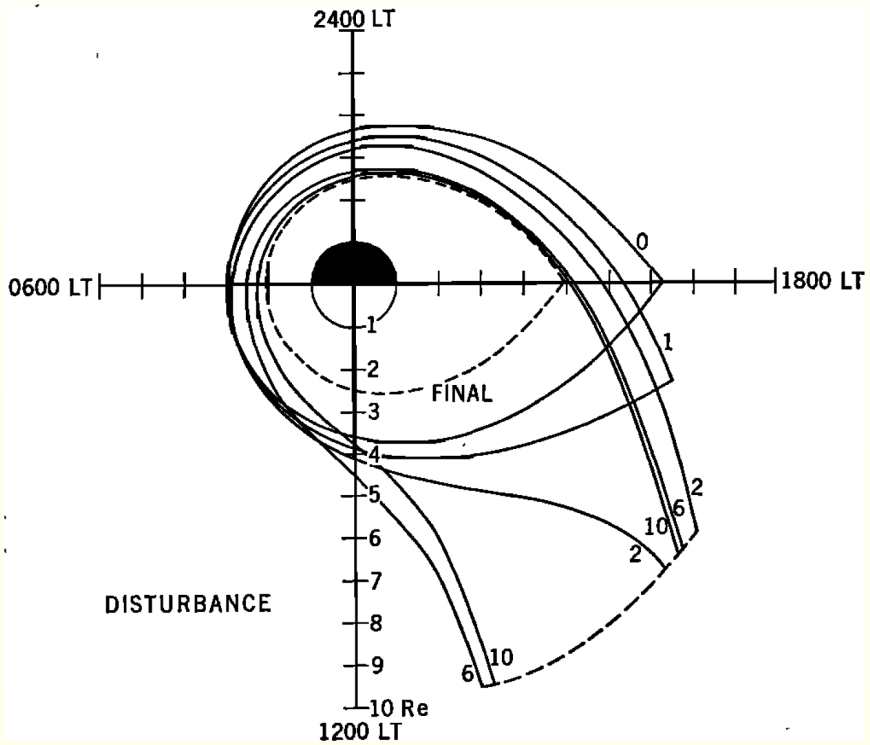
CTIPe (Maruyama et al., GRL 32, 2005)



PLASMASPHERE DYNAMICS

stormtime response (Grebowsky, JGR, 1970)





SAMI3 PLASMASPHERE STUDY

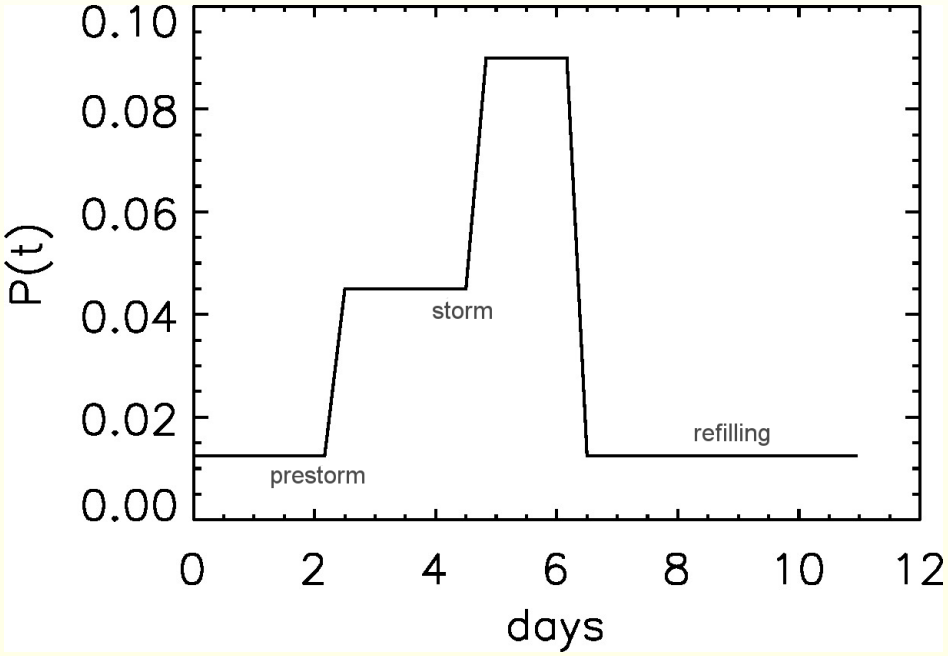
corotation/vsmc potentials (Huba and Krall, GRL, 2013)

- corotation potential

$$\Phi_{\rm cor} = -92/r({\rm kV})$$

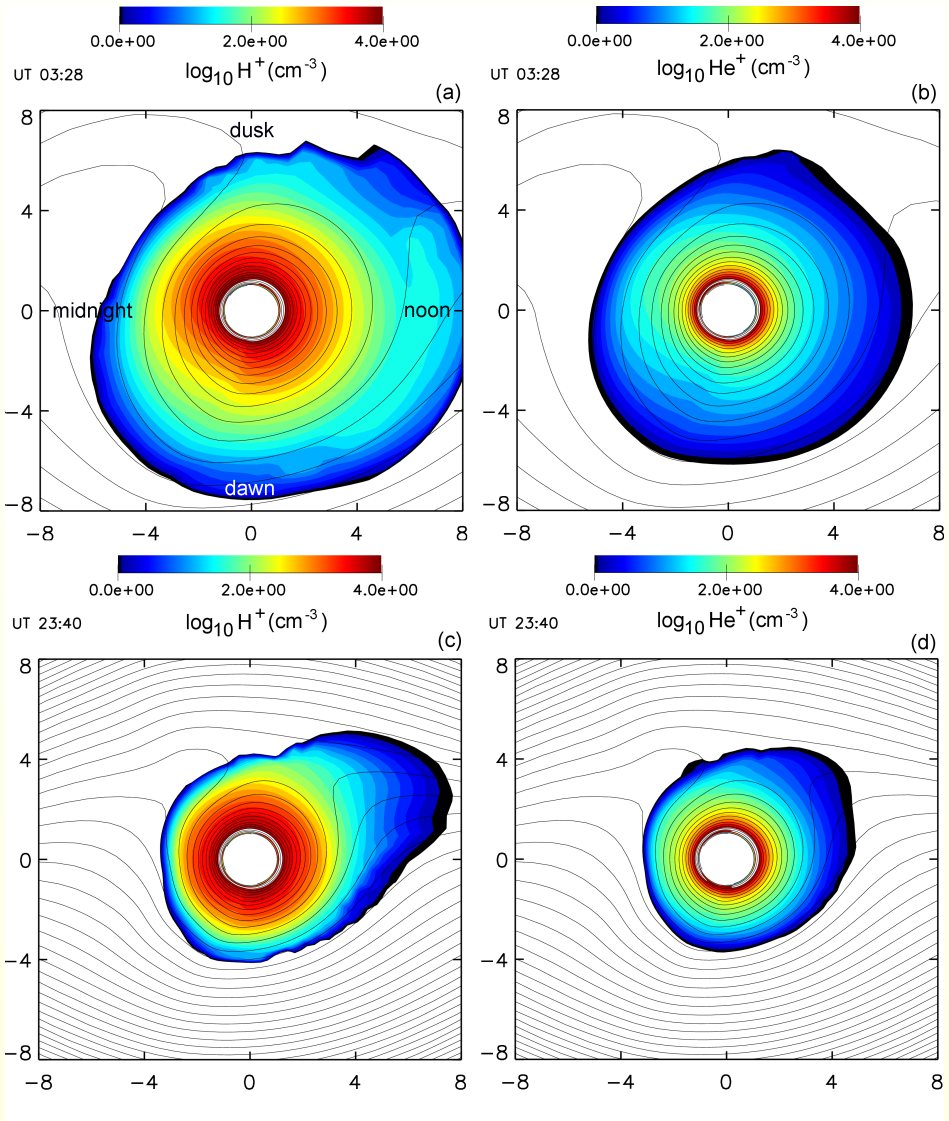
- volland/stern/maynard/chen potential $(K_p = 6)$

$$\Phi_{\rm vsmc} = Ar^2 \sin(\phi) \quad A = \frac{P(t)}{(1. - 0.159K_p + 0.0093K_p^2)^3}({\rm kV})$$



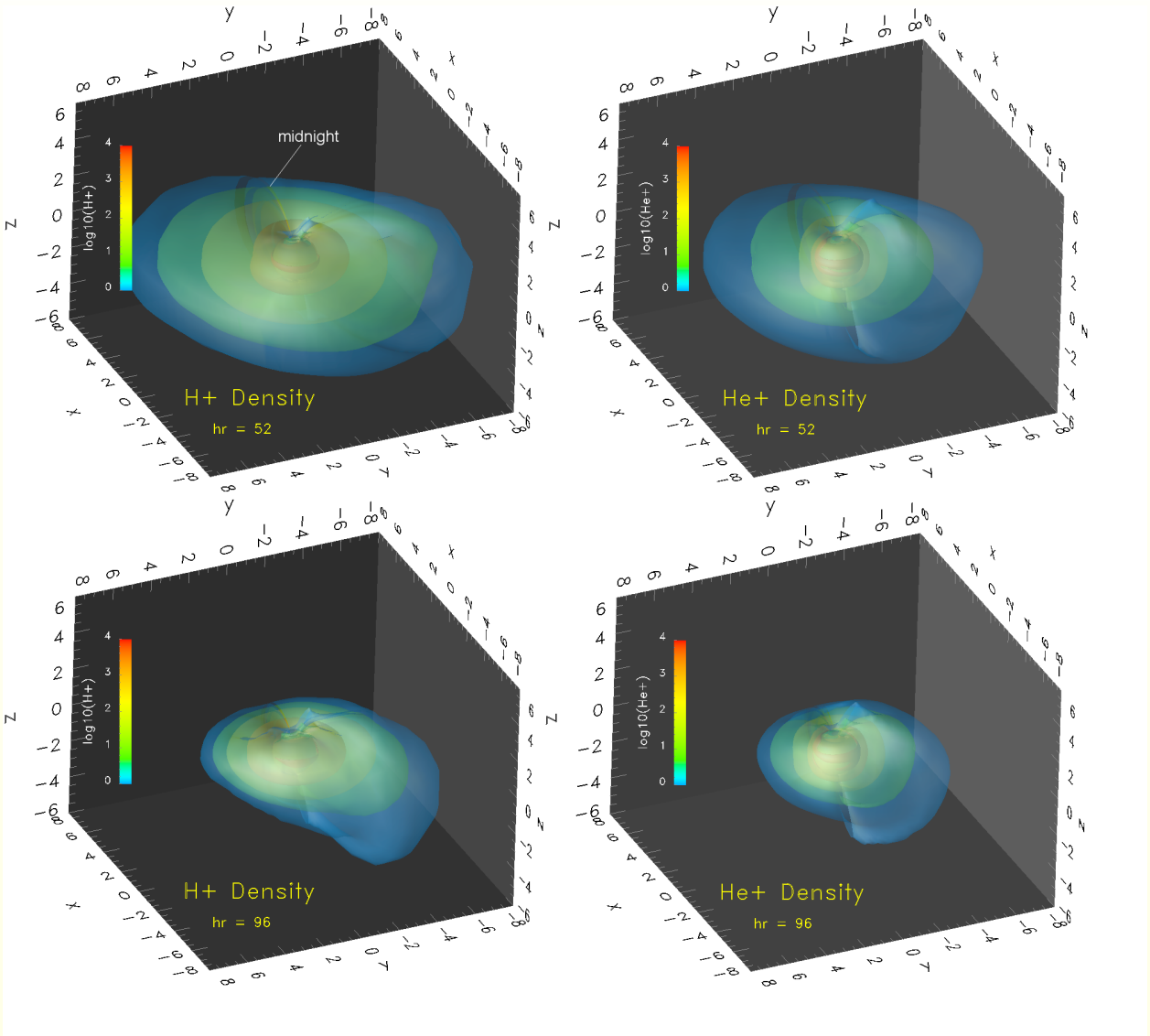
H^+/He^+ CONTOURS

hydrogen / helium ion density contours at t = 52 hrs and 96 hrs in equatorial plane



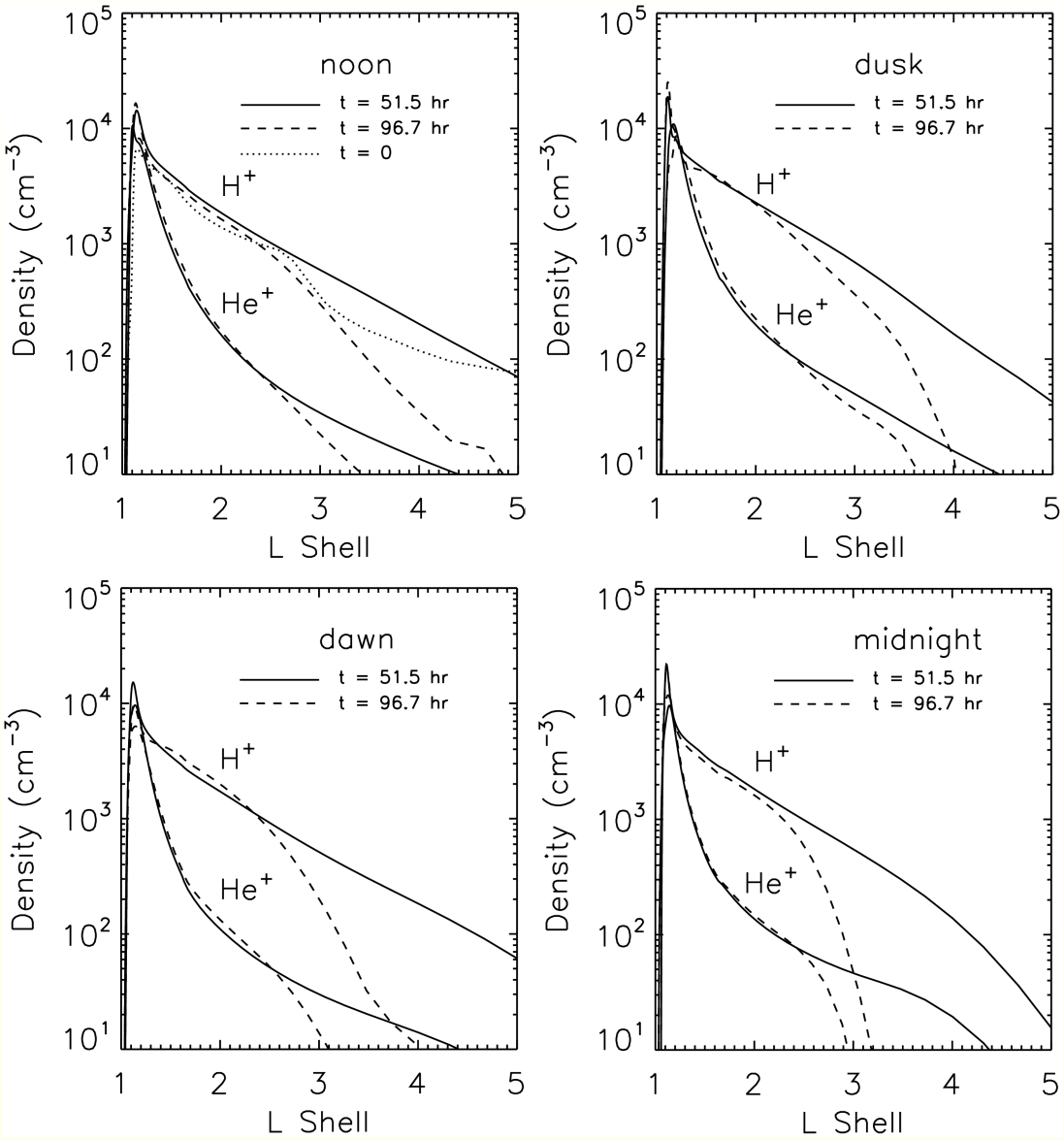
H^+/He^+ ISOSURFACES

electron density isosurfaces at t = 52 hrs and 96 hrs in equatorial plane



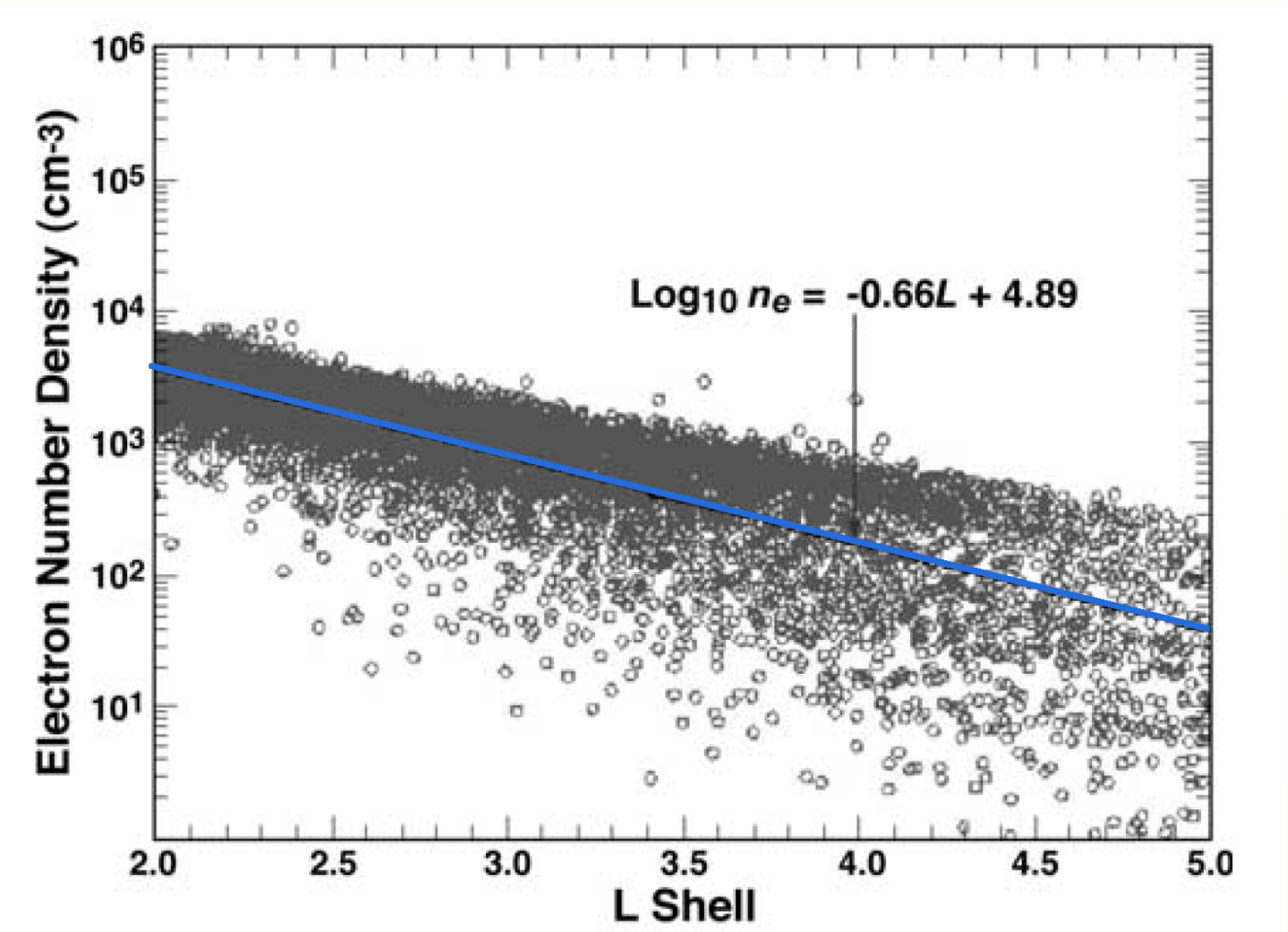
H^+/He^+ PROFILES

line plots of hydrogen and helium ion density vs L shell



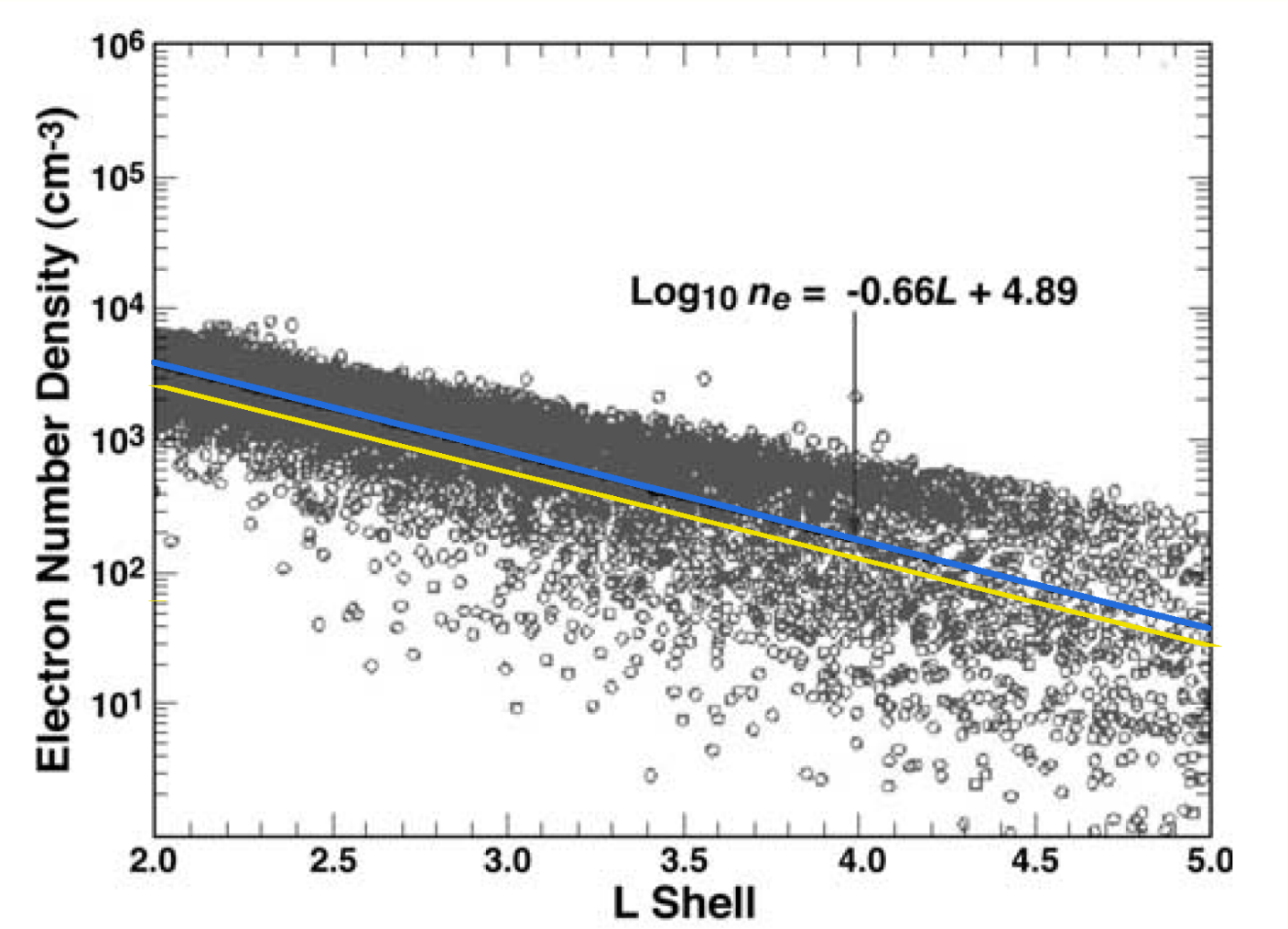
ELECTRON DENSITY DATA

from Berube et al., JGR, 2005



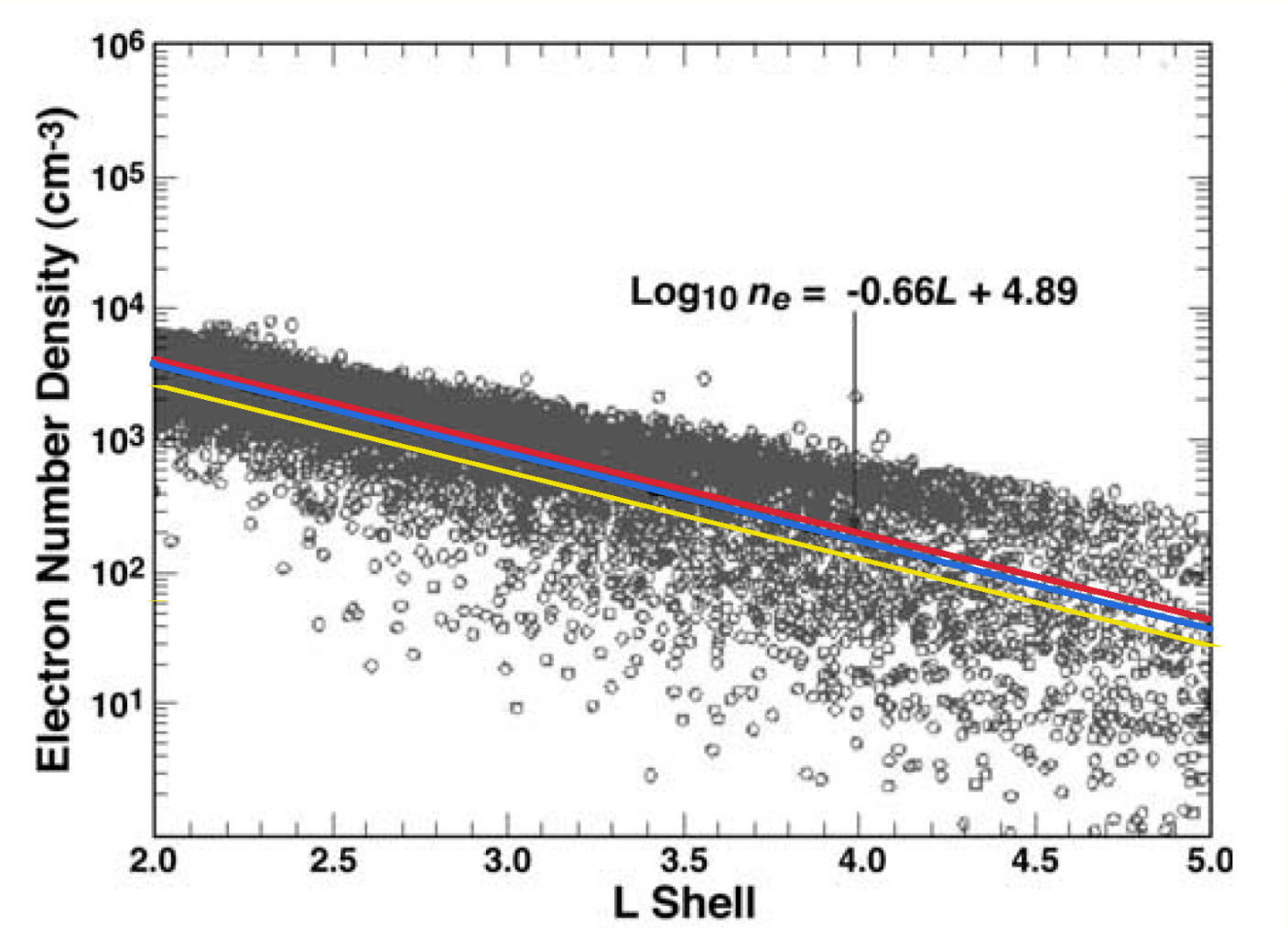
ELECTRON DENSITY AND SAMI3 DATA

original simulation



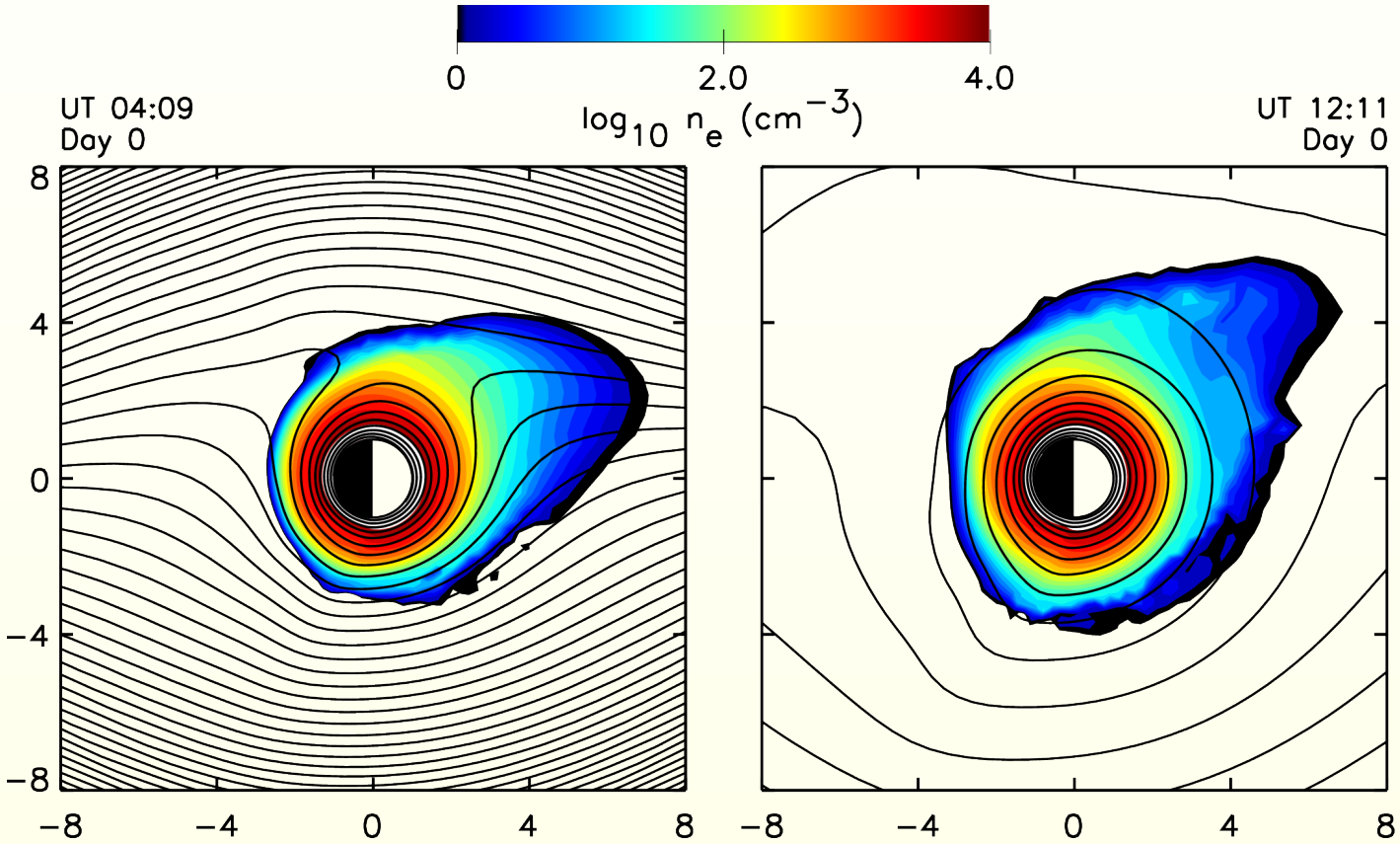
ELECTRON DENSITY AND SAMI3 DATA

hotter electrons



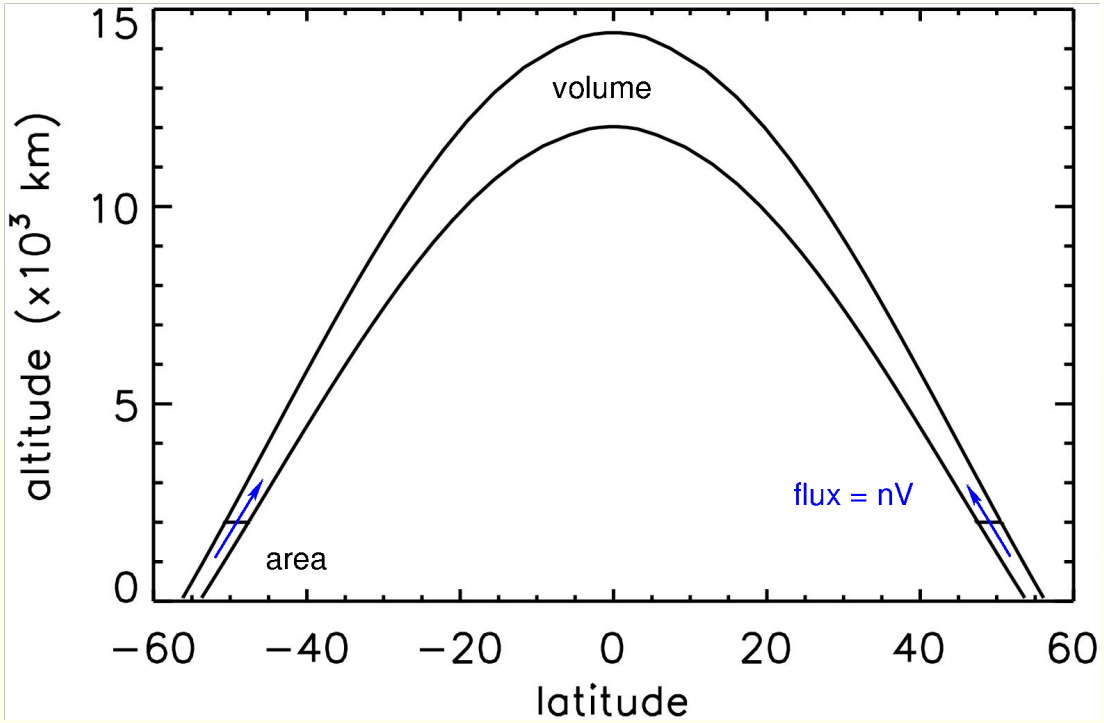
REFILLING

storm time to quiet time



PLASMASPHERE REFILLING

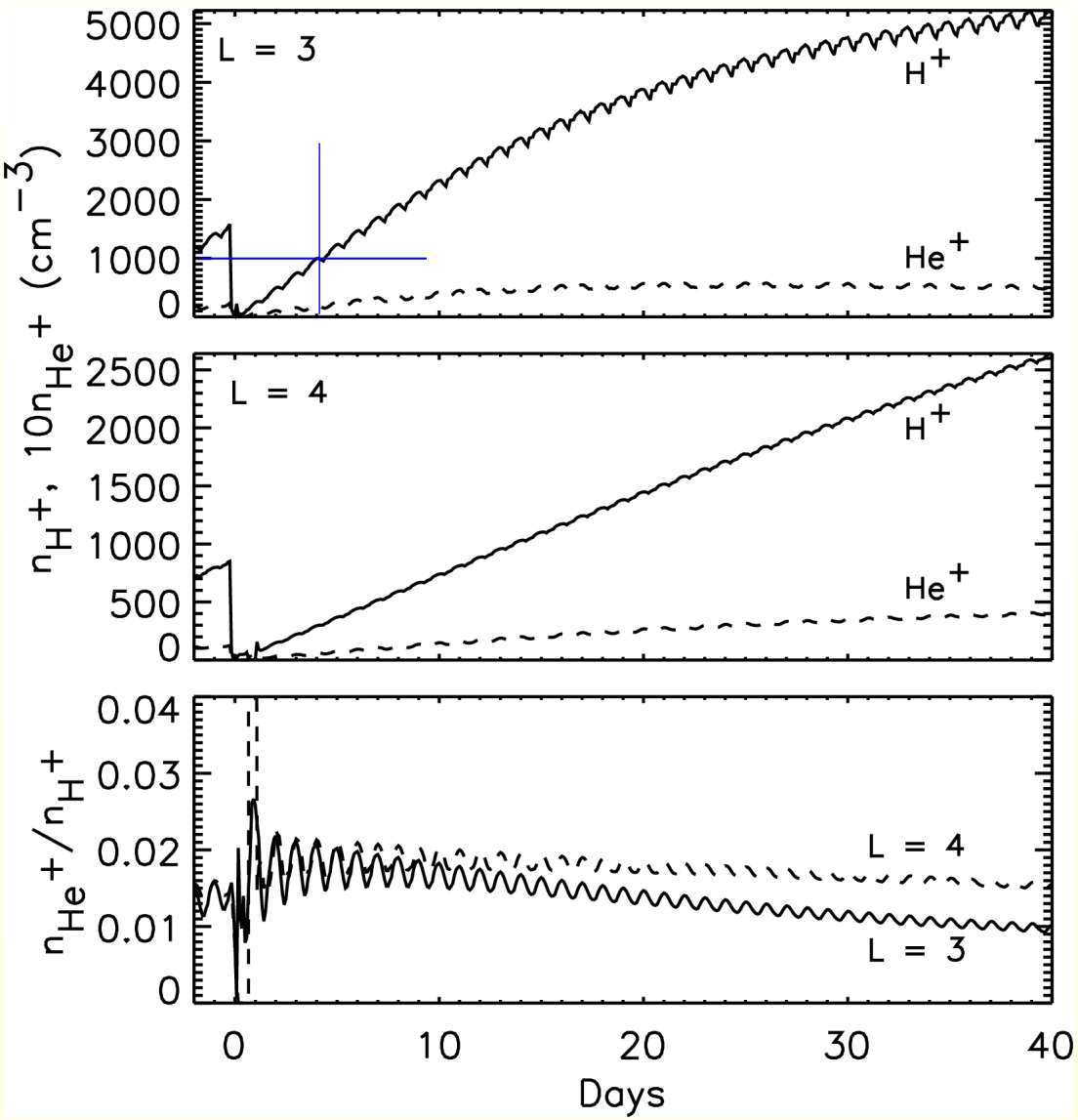
back-of-the envelope calculation



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

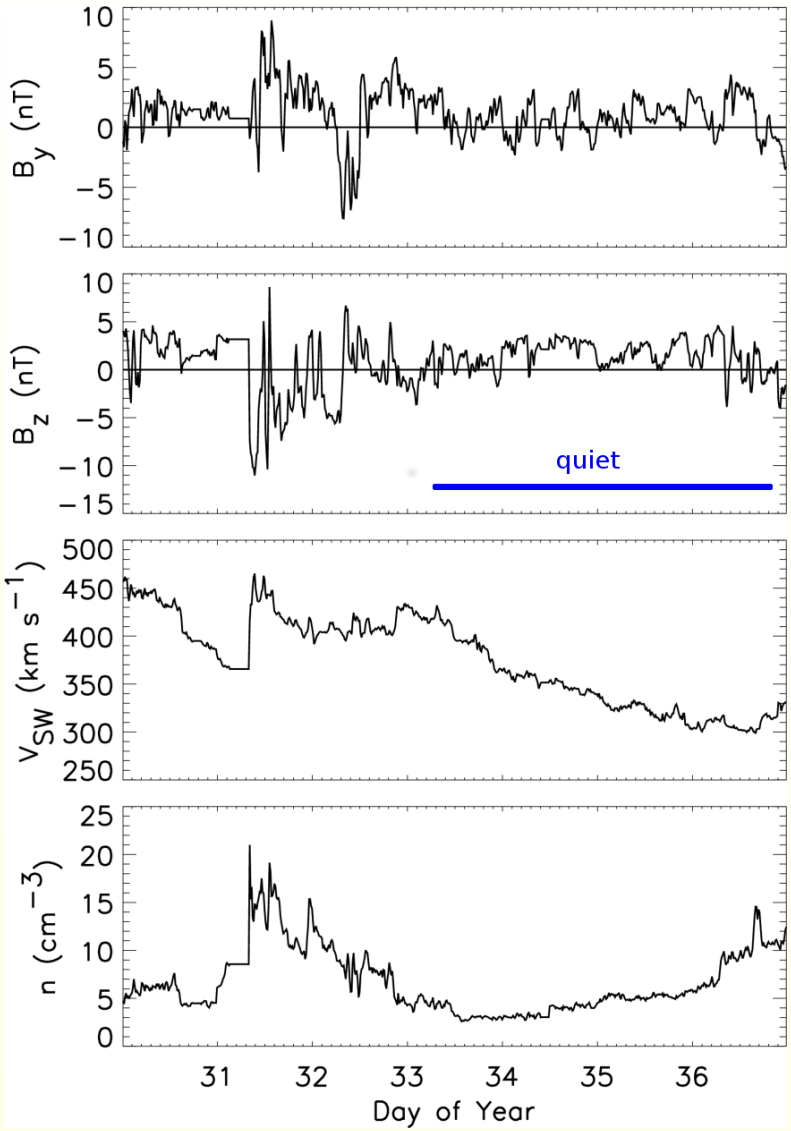
PLASMASPHERE REFILLING

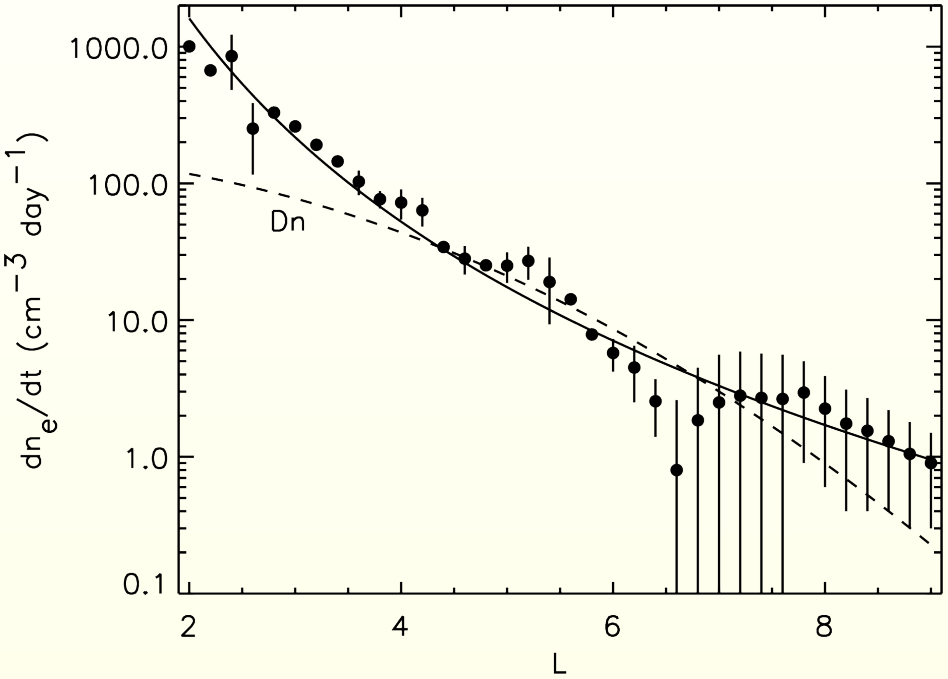
consistent with Krall et al., ANGEO, 2008



FEB 2001 STORM

refilling: solar wind data → Weimer model

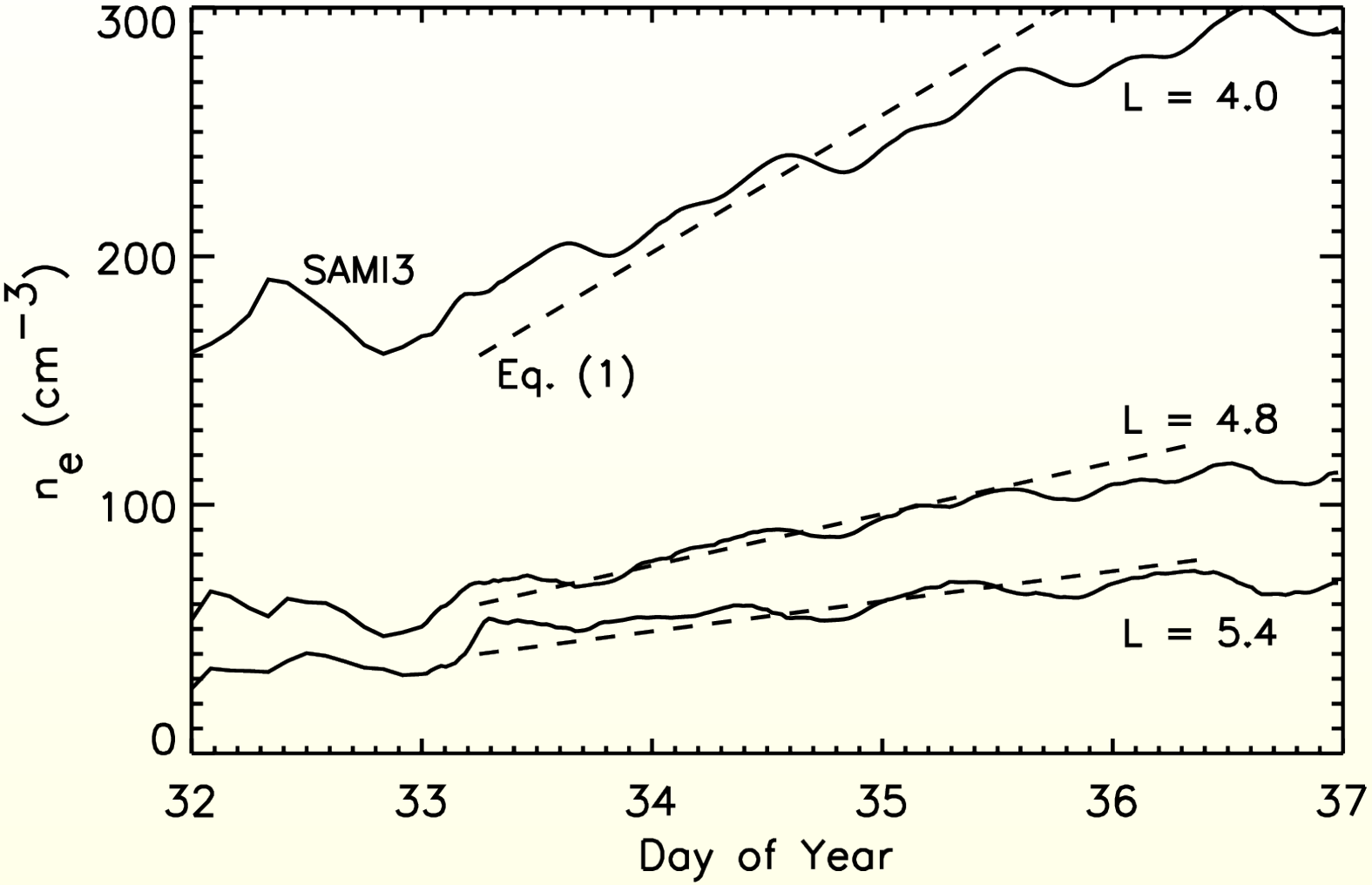




Denton et al, *J. Geophys. Res.*, 2012

SAMI3 REFILLING

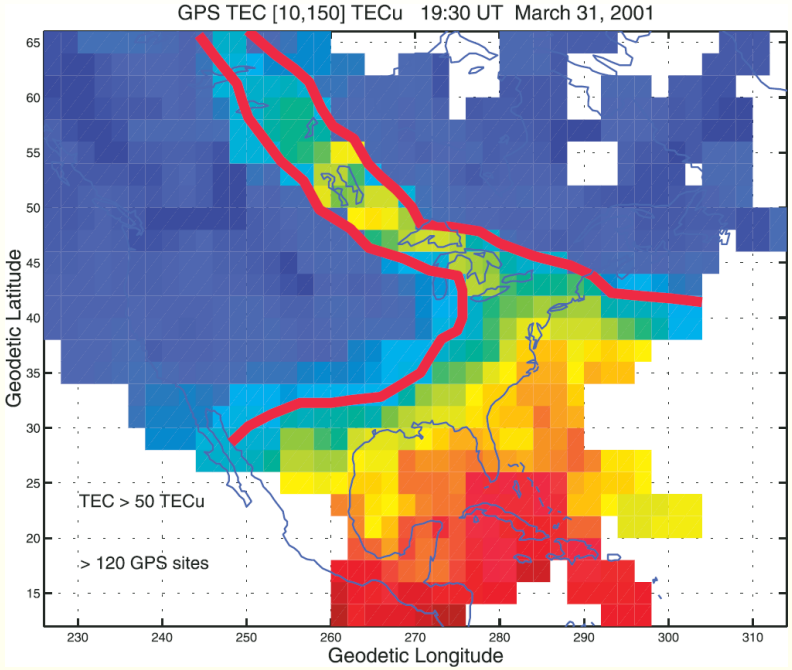
use Weimer model (Krall and Huba, GRL, 2013; Krall et al., JGR, in press, 2014)

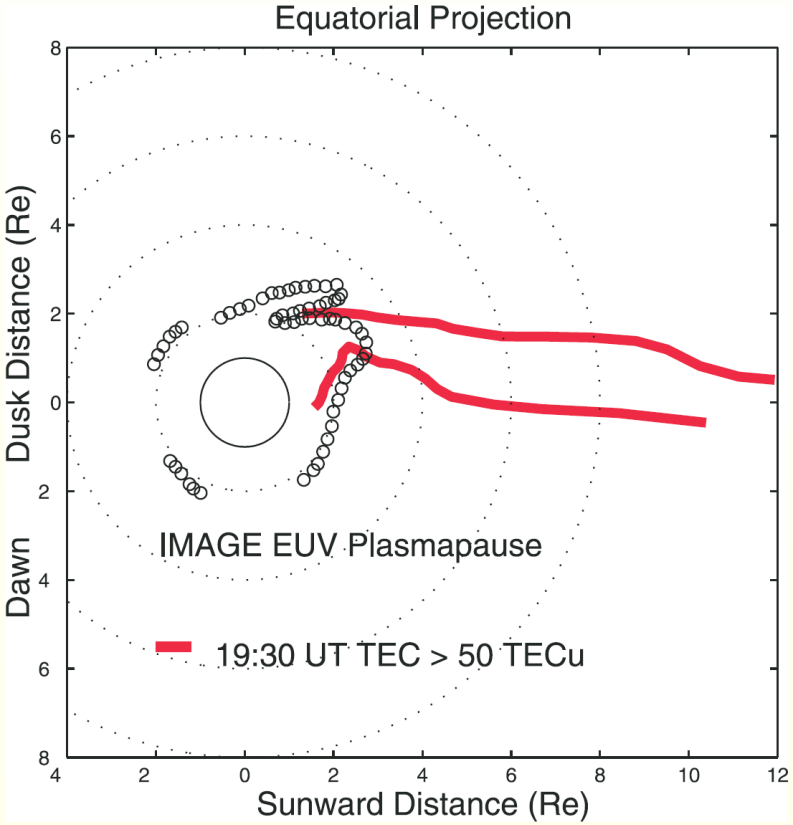


$$dn_e/dt = 3.81(6.8/L)^{4.94}\mathrm{cm}^{-3}\mathrm{day}^{-1} \quad (1)$$

IONOSPHERE/PLASMASPHERE SIGNATURES

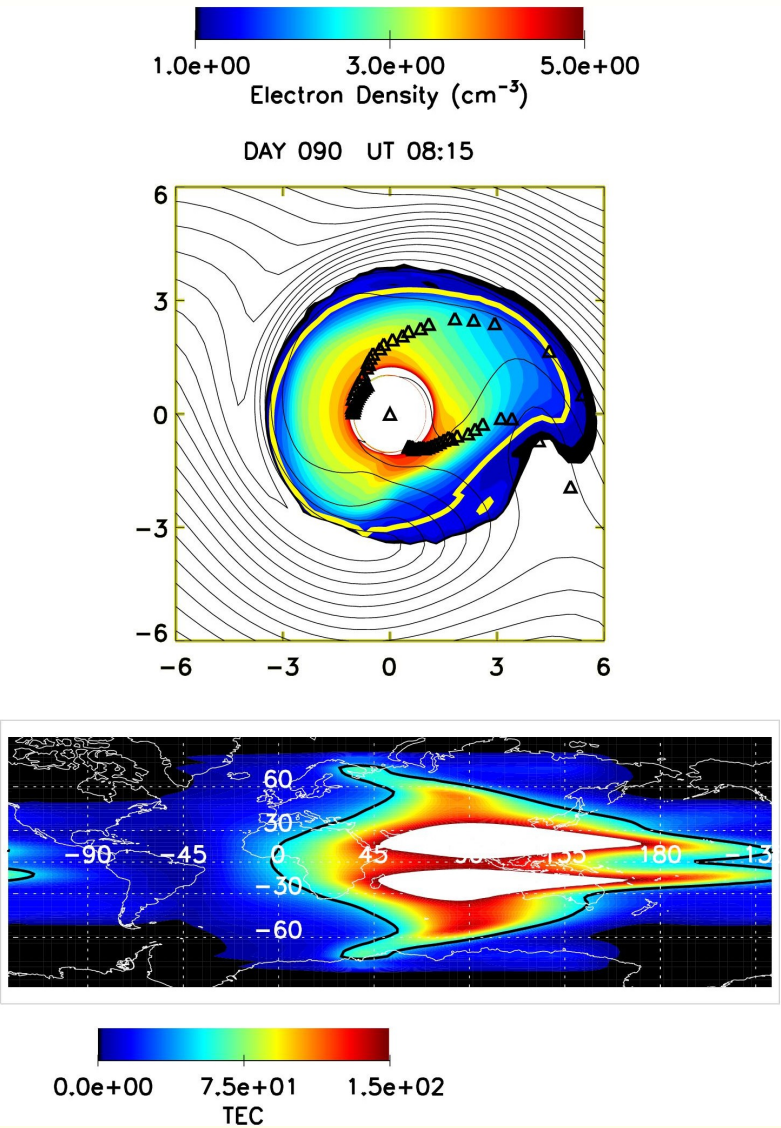
march 31, 2001 storm: Foster et al., *Geophys. Res. Lett.*, 2002





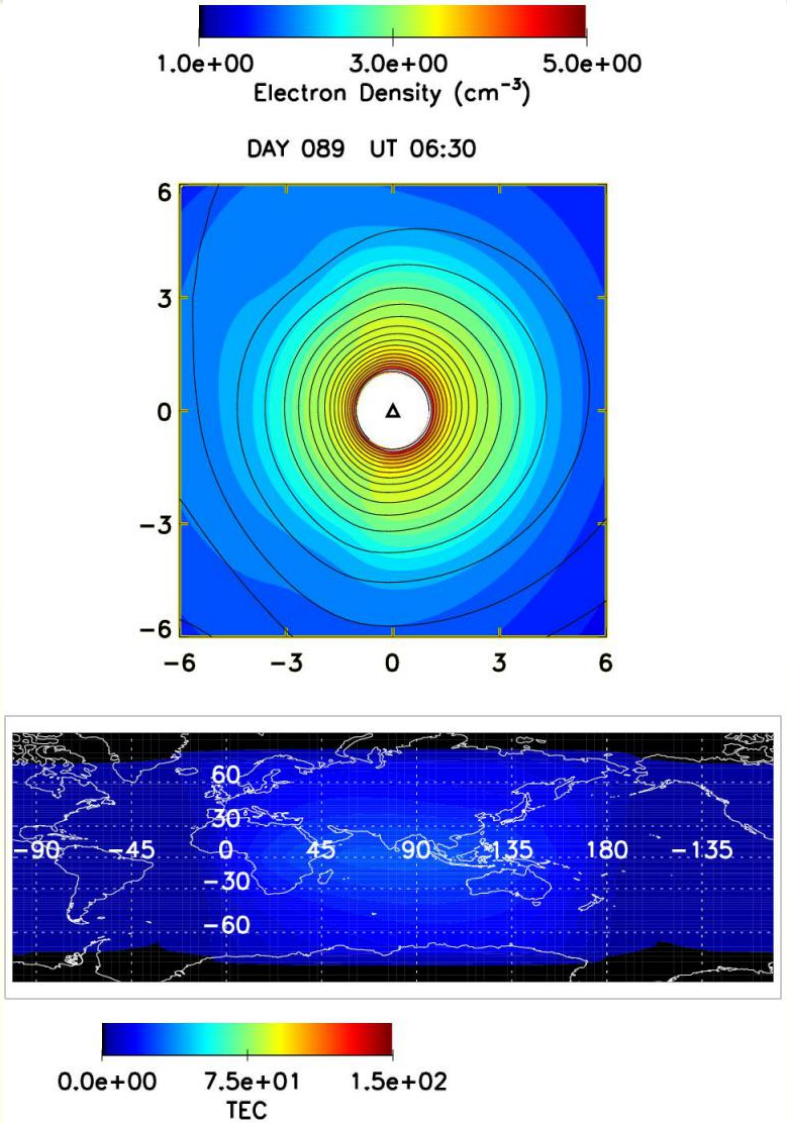
SAMI3/RCM

march 29, 2001 storm



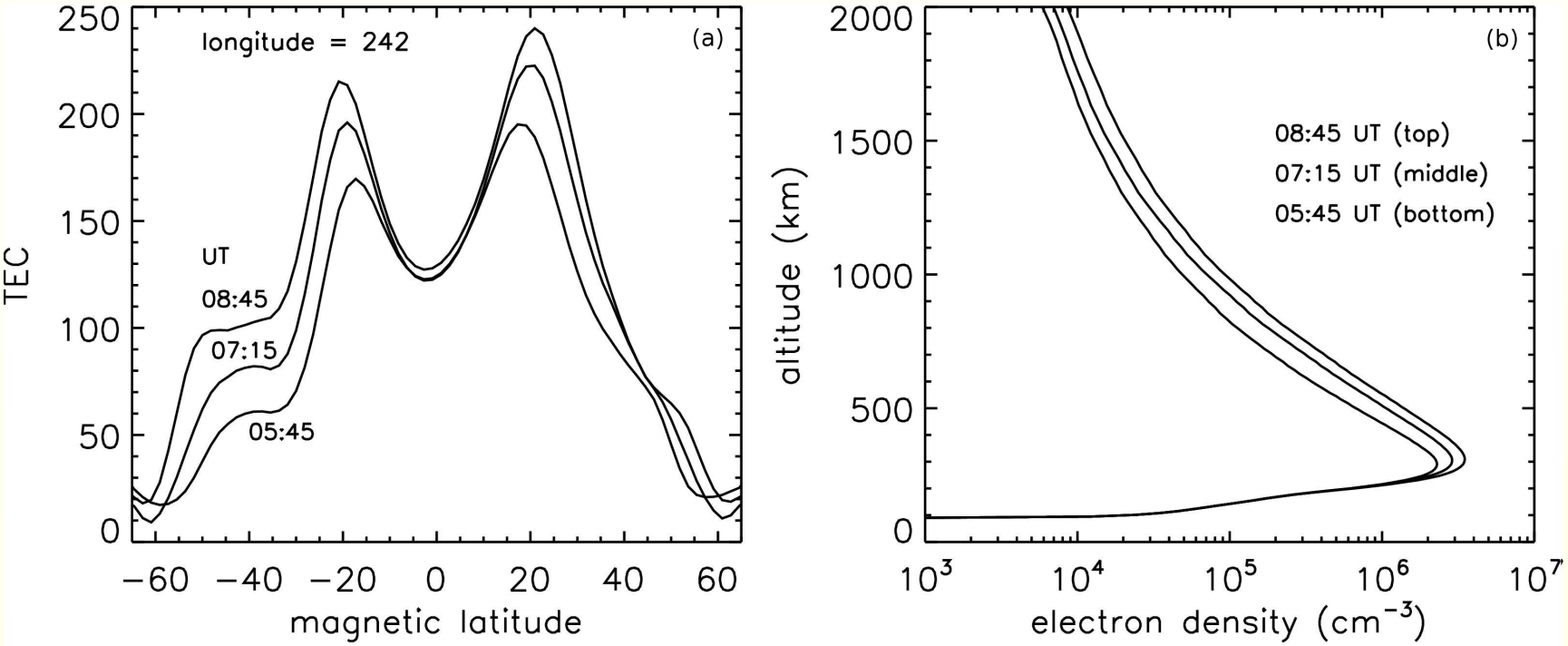
SAMI3/RCM

march 29, 2001 storm



SAMI3/RCM

march 29, 2001 storm - impact on TEC and electron density profile



SUMMARY

- 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