PLASMA IRREGULARITIES IN THE EARTH'S IONOSPHERE AND PLASMASPHERE

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MIPSE Seminar
University of Michigan
Ann Arbor, MI
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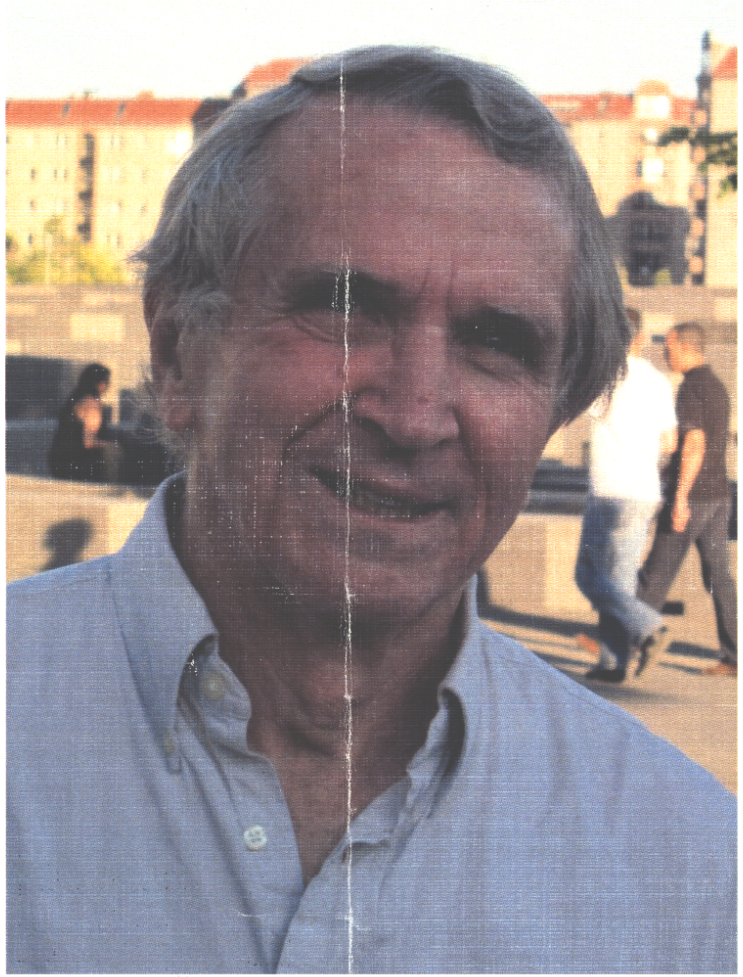
with H.-L. Liu (HAO/NCAR), E. Becker (NWRA), and J. Krall (NRL)

co-author of SAMI2/3

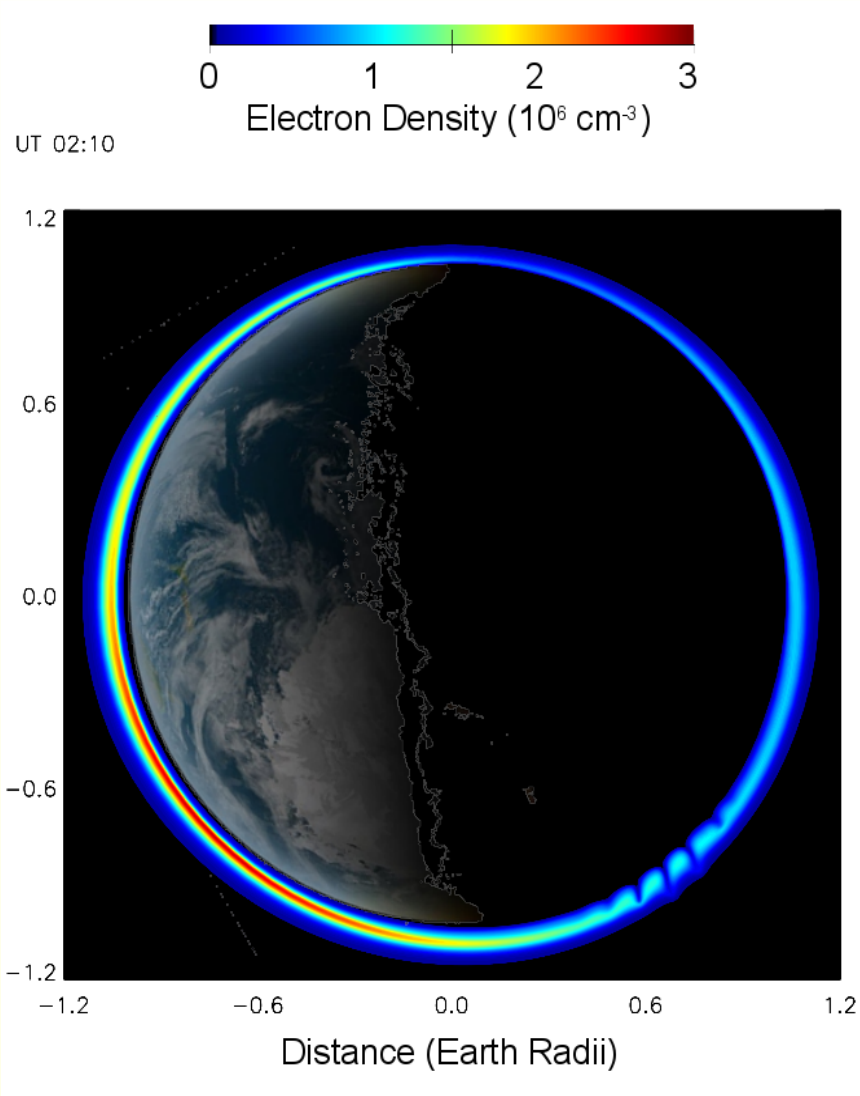
Glenn Joyce



June 24, 1939 – December 4, 2011

THE IONOSPHERE

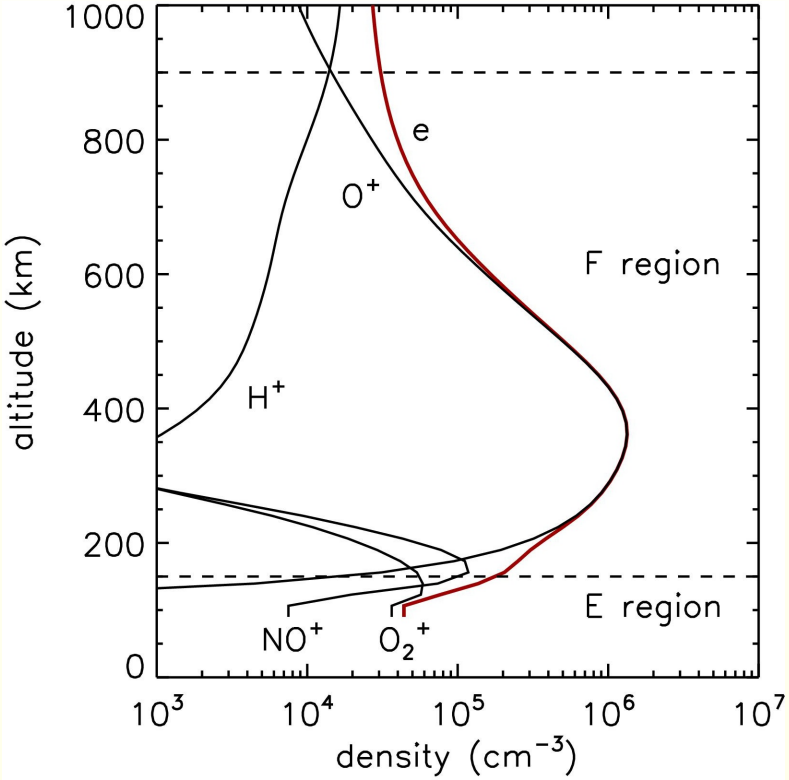
weakly ionized gas surrounding the earth

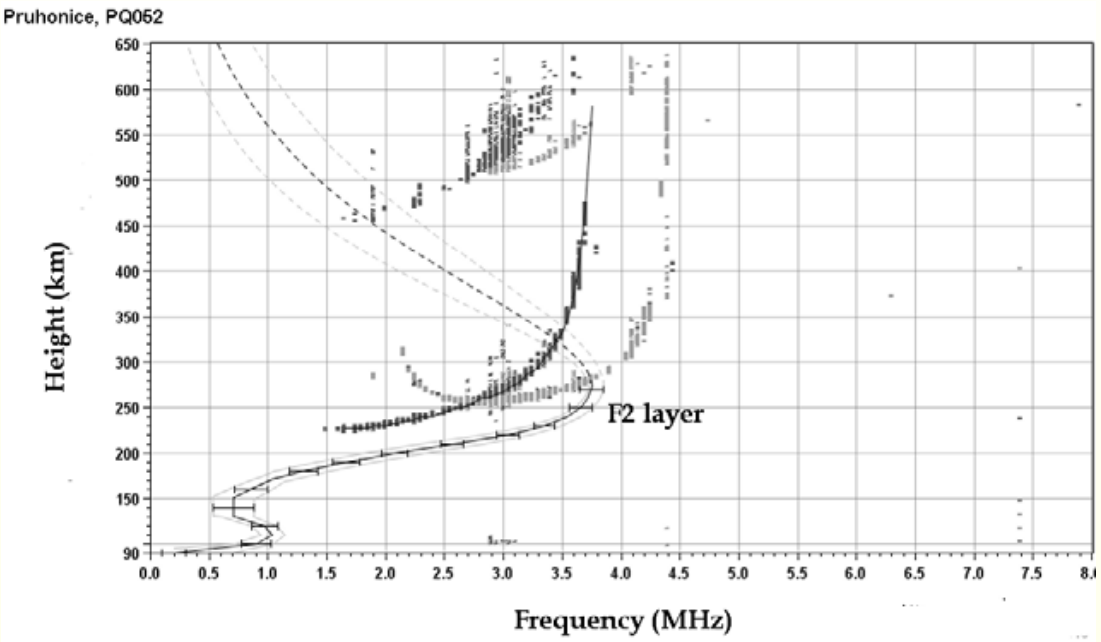


- neutrals ionized by sun's EUV radiation (10Å- 1000Å)
- extends from 90 km to 1000s km
- $n_e \lesssim 10^6$ cm^{-3} but $n_n \lesssim 10^{10}$ cm^{-3}
- multi-ion plasma
- very low β plasma: $\beta \sim 10^{-5}$
- $T \lesssim 3000$K (or .3 eV)
- anisotropic conductivities: $\sigma_{\parallel} >> \sigma_{\perp}$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

NOMINAL PLASMA PROFILE AND IONOGRAM

ion density as a function of altitude





(Knížová and Mošna, 2011)

THE BEGINNING RE STRUCTURE

Booker and Wells, *J. Geophys. Res. 43*, 249 (1938)

SCATTERING OF RADIO WAVES BY THE *F*-REGION OF THE IONOSPHERE

By H. G. Booker and H. W. Wells

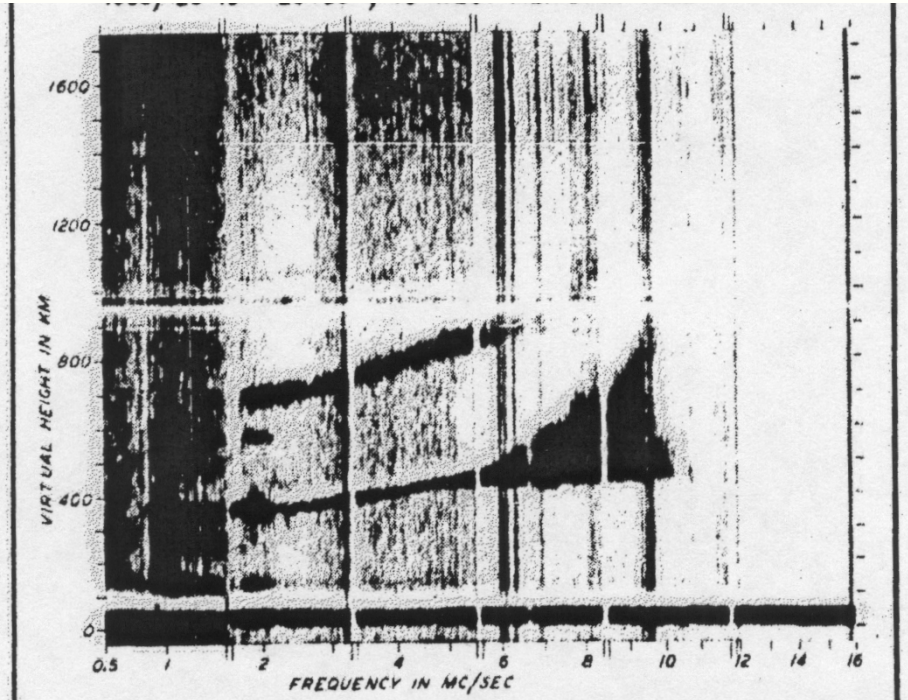


FIG. 2—RECORD SHOWING REGULAR AND DIFFUSE F-REGION ECHOES, HUANCAYO MAGNETIC OBSERVATORY, FEBRUARY 23, 1938, $21^h30^m-21^h45^m$, 75° WEST MERIDIAN HOURS

"We therefore interpret Figure 3-A as indicating existence in the F-region of irregularities in electron-density, the linear dimensions of which are of the order of 25 meters."

BUBBLE CARTOON

Woodman and LaHoz, *J. Geophys. Res. 81*, 5447 (1976)

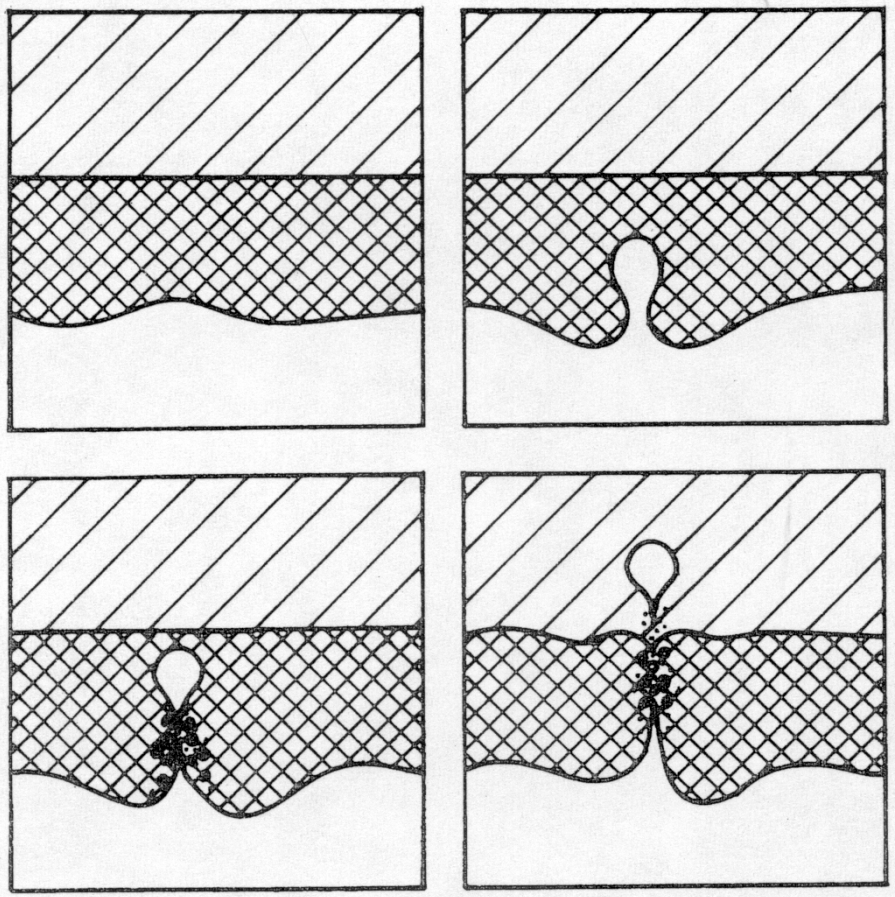
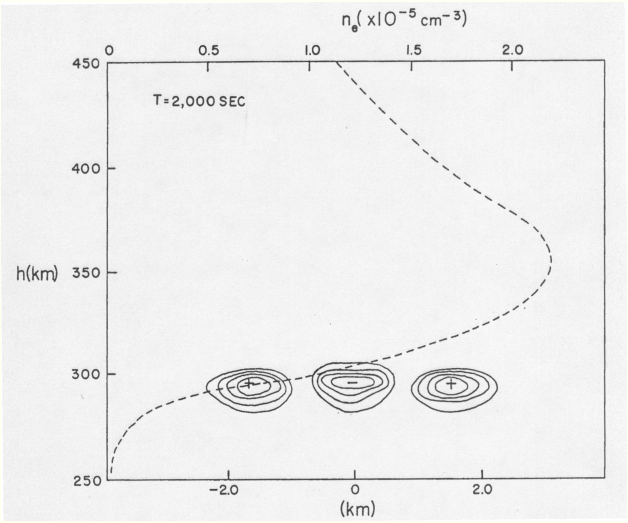
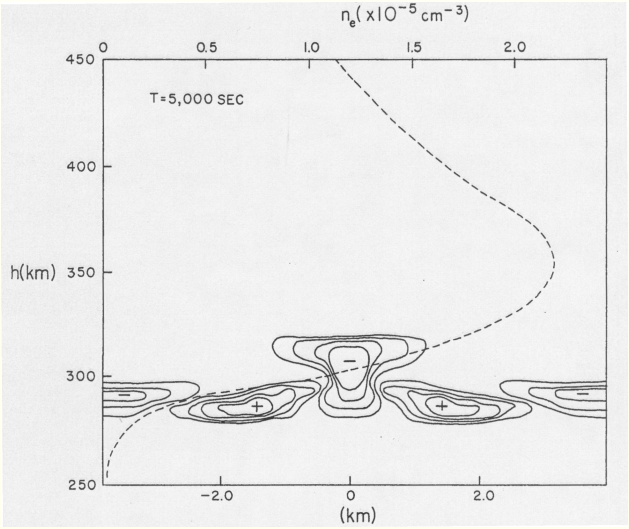


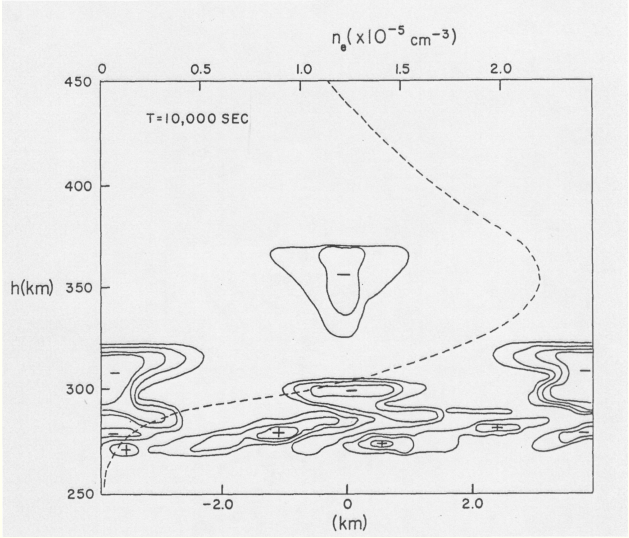
Fig. 9. Schematic representation of a three-density model of the ionosphere showing the formation of a bubble of low electron density and its propagation to the gravitationally stable top. The middle fluid is heavier than the top, and the top fluid heavier than the bottom.

FIRST BUBBLE SIMULATION

Scannapieco and Ossakow, *Geophys. Res. Lett. 3*, 451 (1976)







EQUATORIAL SPREAD F (ESF)

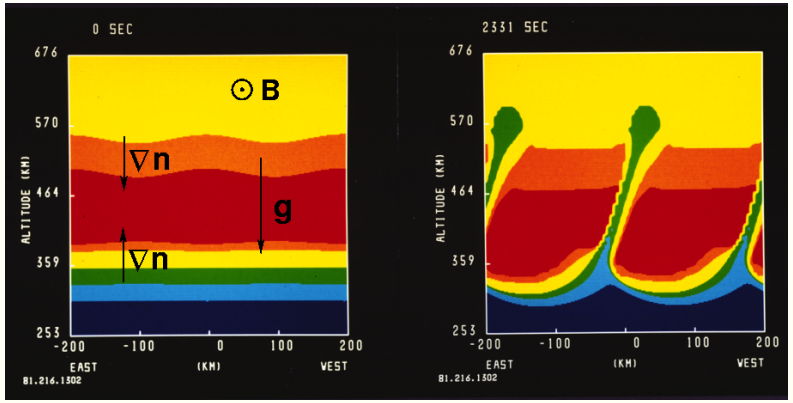
- equatorial spread F is the development of ionospheric irregularities in the nighttime equatorial ionosphere.
- Rayleigh-Taylor-like instability
- linear growth rate (*Sultan*, 1996):

$$\gamma = \frac{\Sigma_P^F}{\Sigma_P^E + \Sigma_P^F} \frac{1}{L_n} \left(V_p + U_n^P + g_L / \nu_{in}^{eff} \right) - R_T$$

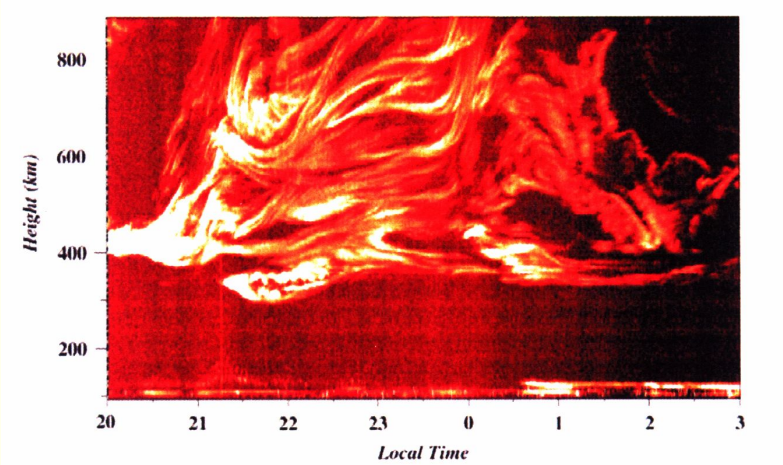
- plasma 'bubbles' nonlinearly penetrate the topside ionosphere
- range of electron density irregularities: 10s cm - 10s km

  'hierarchy of instabilities'

  (*Haerendel*, 1973)



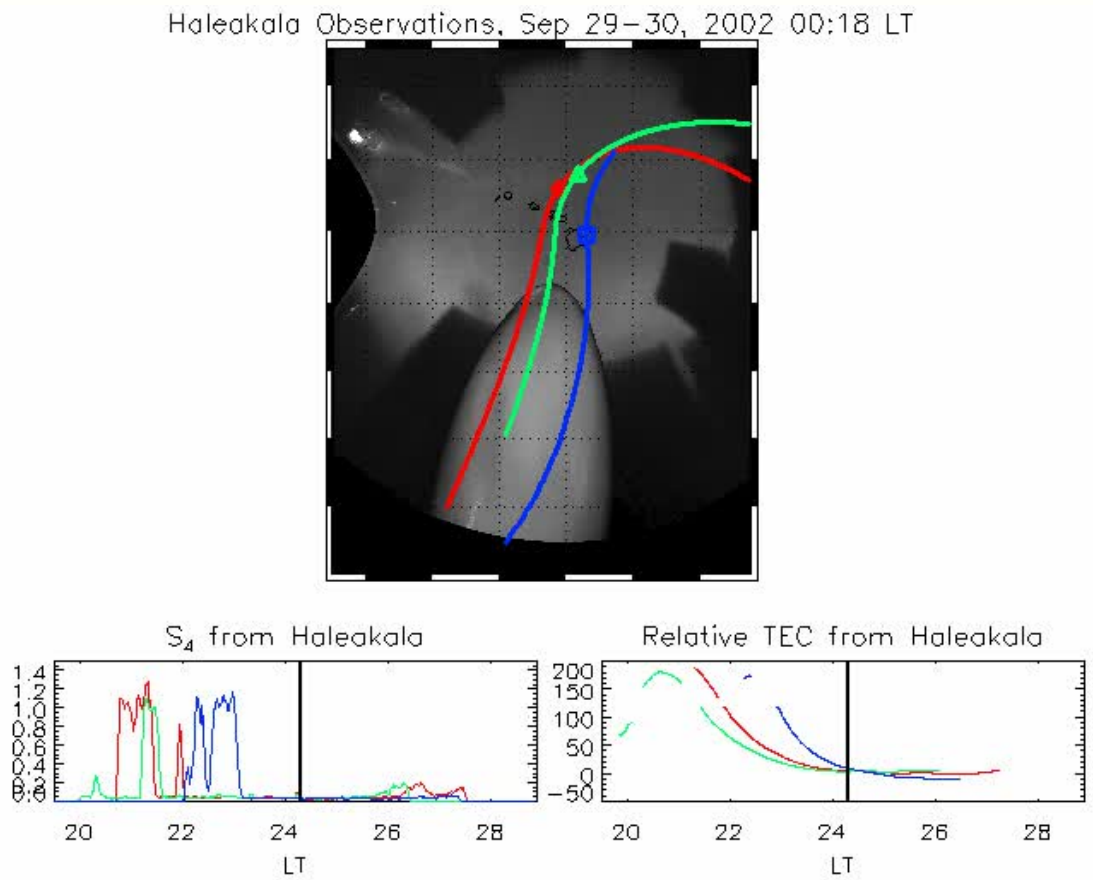
Computer simulation of ESF (*Zalesak et al.*, 1982).



Radar backscatter from 3m irregularities at Jicamarca (*Hysell*).

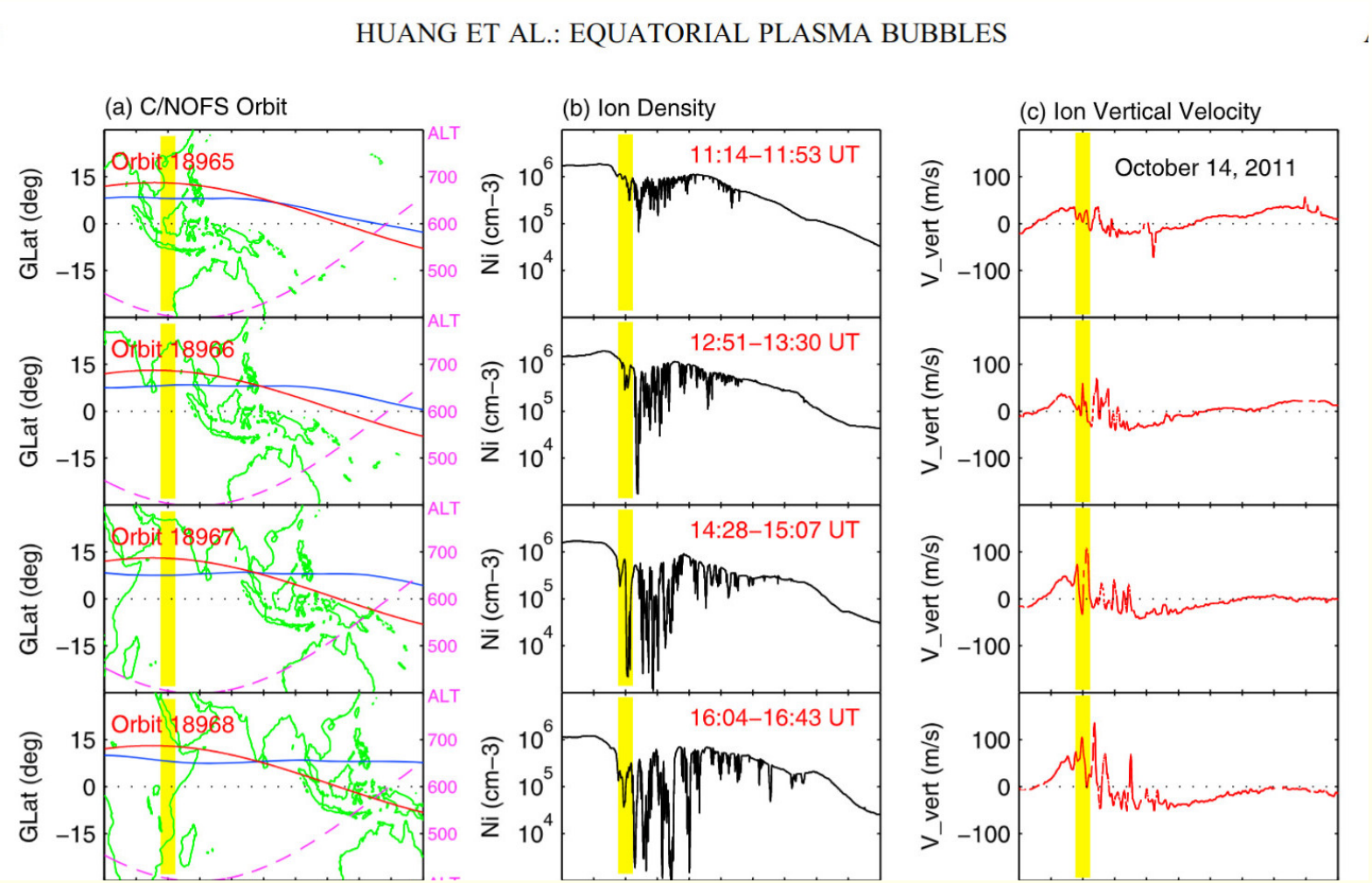
DYNAMIC ESF VISUALIZED

optical emissions from equatorial depletions (courtesy Jon Makela)



CNOF/S SATELLITE MEASUREMENTS

deep plasma depletions / fast upward velocities



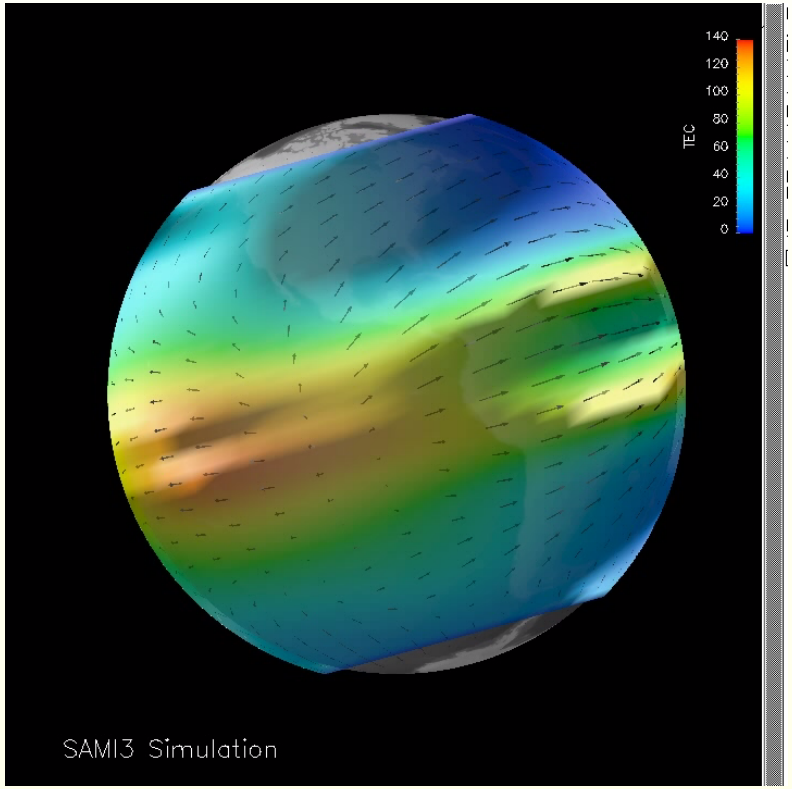
SAMI3

global ionosphere/plasmasphere model (developed at NRL with Glenn Joyce)

- ions: H^+,O^+,He^+,N^+,N_2^+,NO^+,O_2^+
- global model
- vertical and zonal $E \times B$ drift
- neutral species:

  NRLMSISE00/HWM93

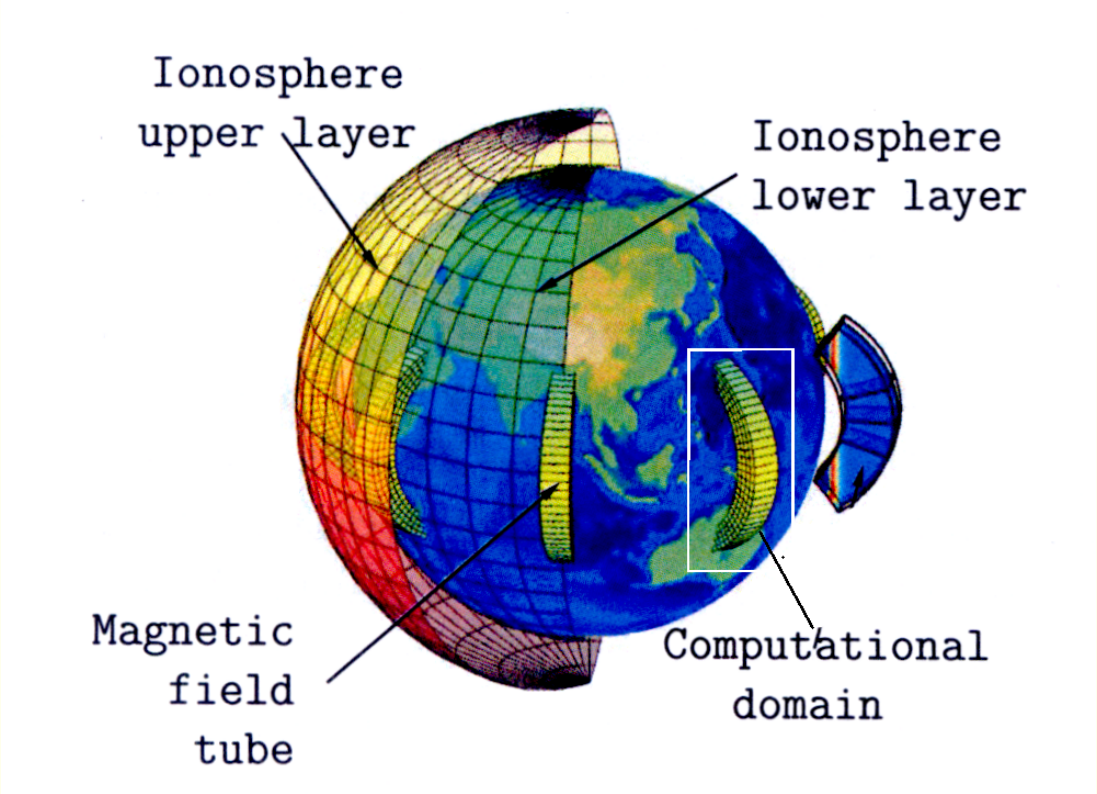
  WACCM-X/HIAMCM/TIEGCM/GITM
- nonorthogonal, nonuniform fixed grid
- solve continuity, velocity, temperature equations
- includes ion inertia along B (important for the collisionless plasmasphere)



SAMI3/ESF WEDGE MODEL

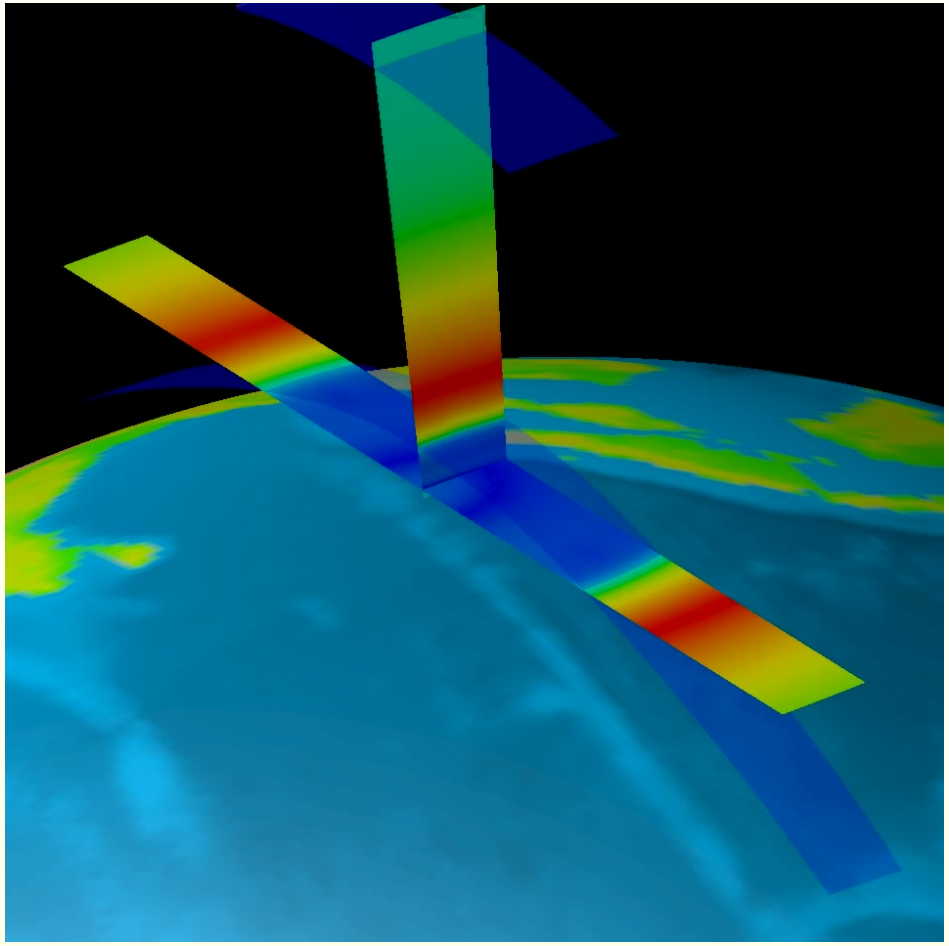
figure from Besse et al. (2006)

- problem:
  global scale 1000s km
  but bubbles $\sim$ 10s km
- grid resolution issue
- simulate limited region in longitude



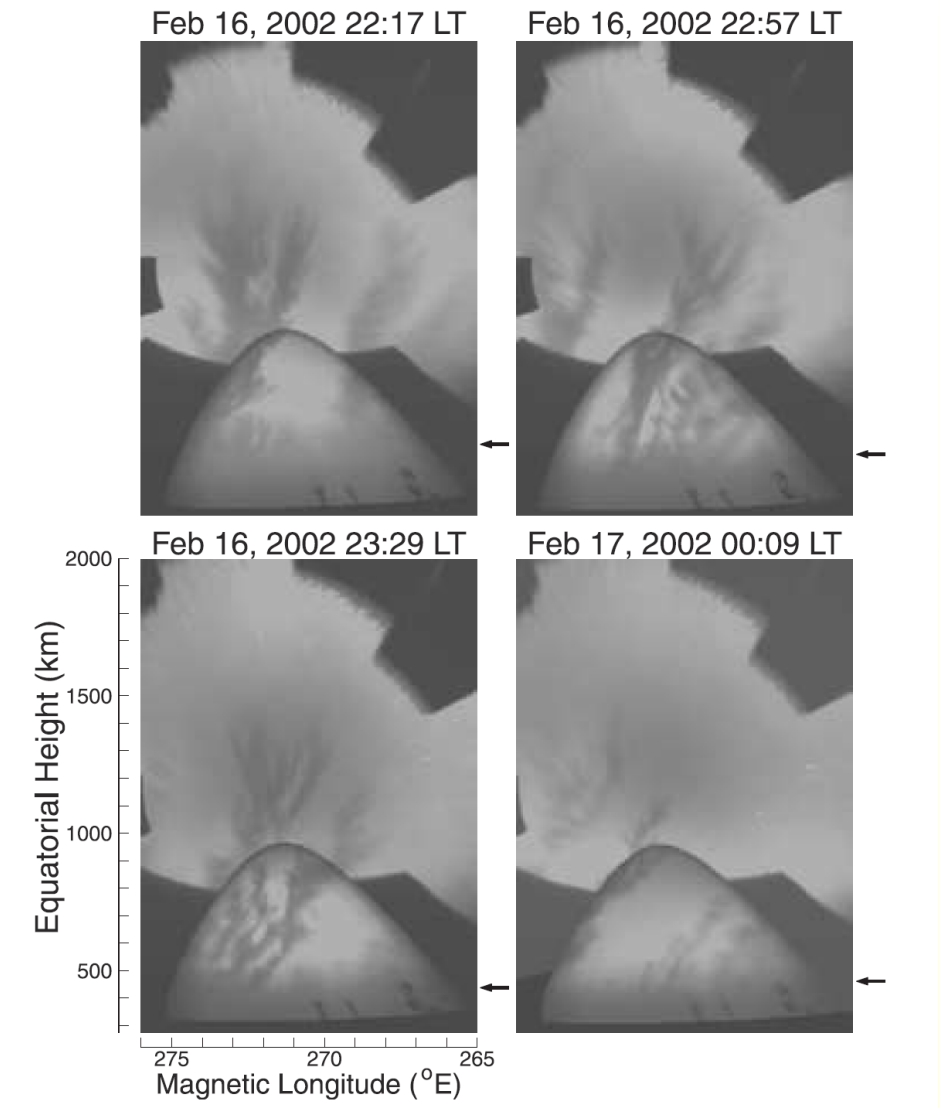
ELECTRON DENSITY

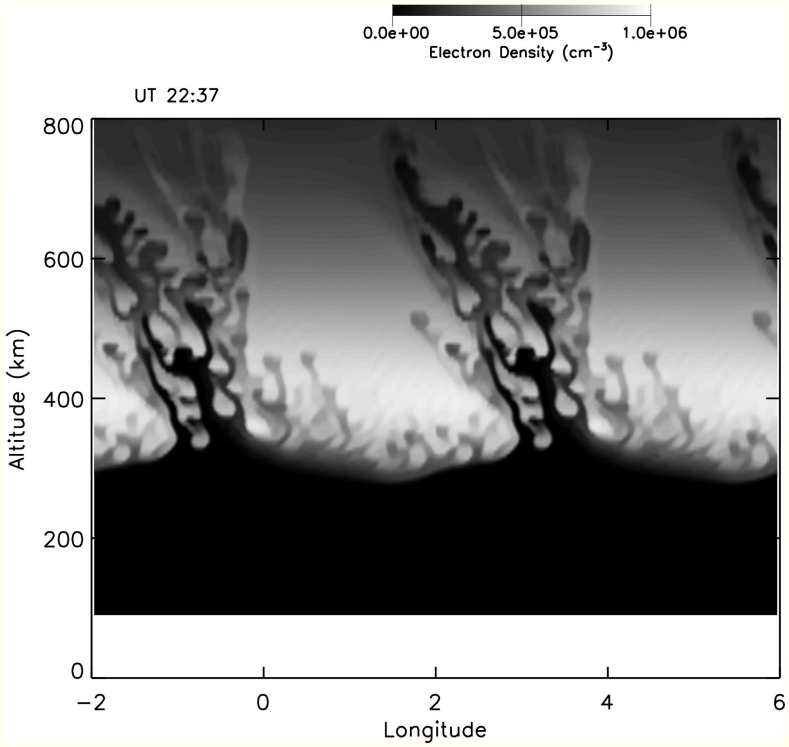
Huba et al., *GRL 35*, L10102, 2008



FLUX-CORRECTED TRANSPORT

4th order partial donor cell method ('visual' data/model comparison)

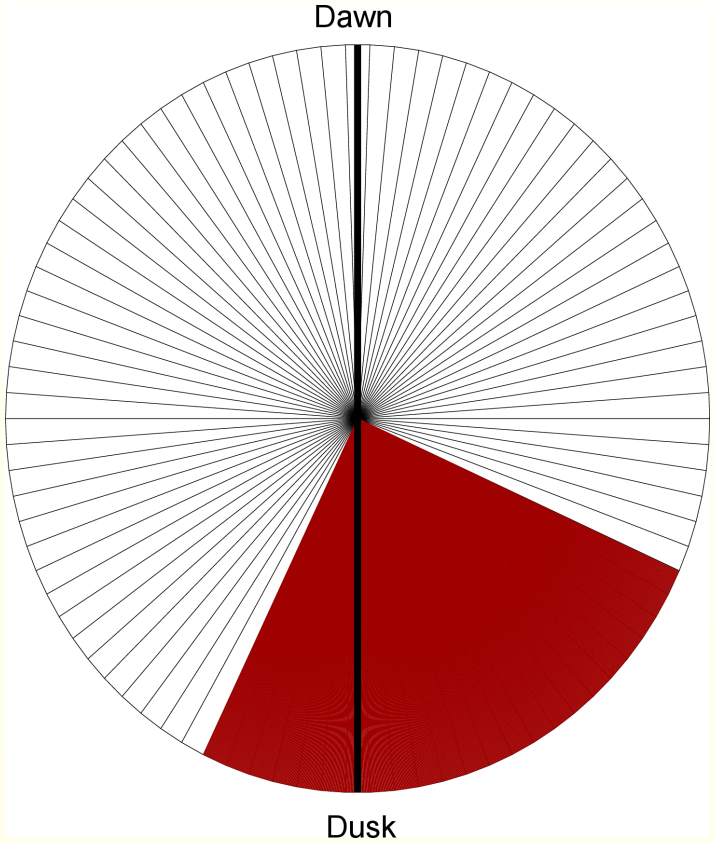




GLOBAL SOLUTION

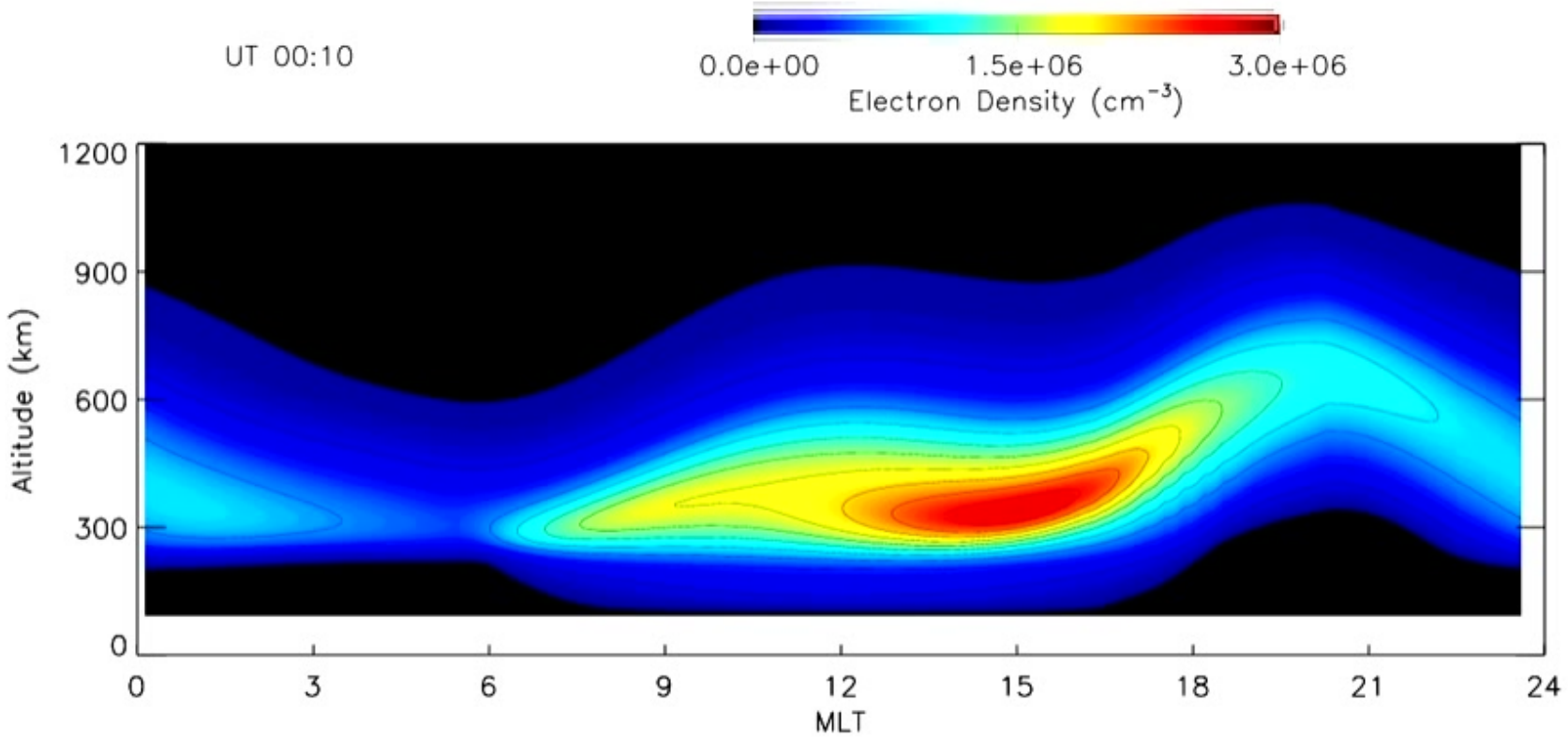
incorporate a high-resolution grid in a global model, i.e., SAMI3

- reference frame: Copernican (sun-fixed: rotating earth)
- coarse mesh: 90 grid points
- zonal resolution $\sim$ 500 km
- high resolution mesh: 956 grid points between $\sim$ 16:30 MLT - 22:30 MLT
- zonal resolution $\sim$ .0625° or $\sim$ 7 km



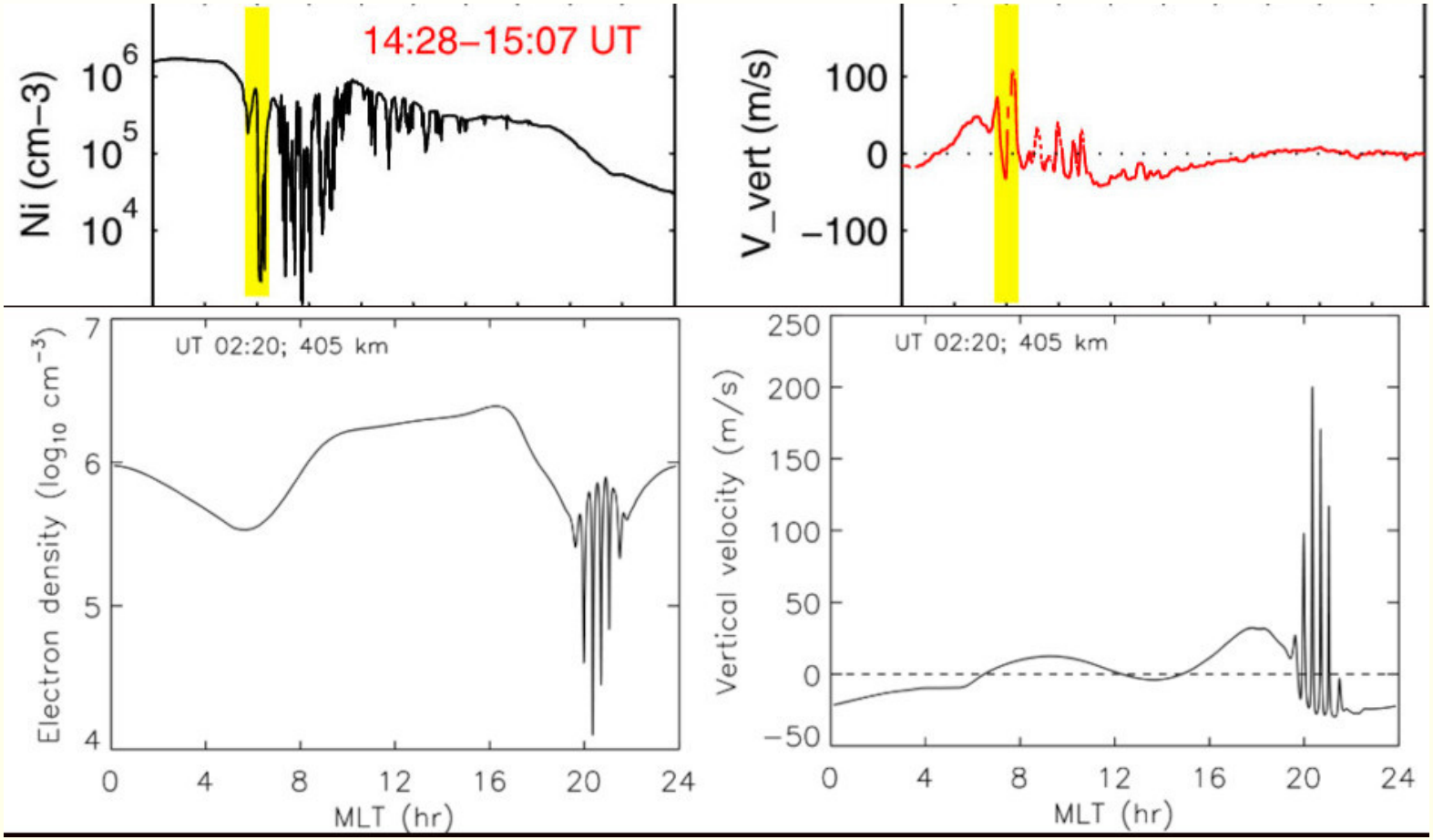
FIRST GLOBAL MODEL OF ESF

Huba and Joyce, *GRL*, 2010



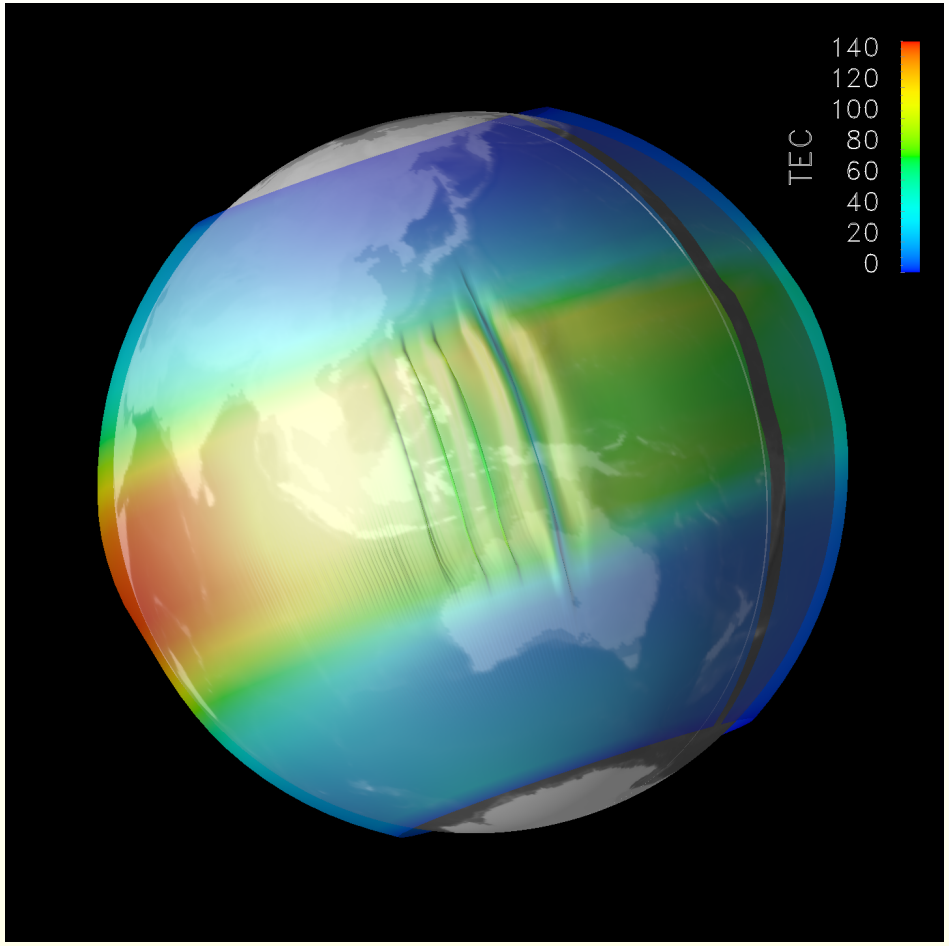
RESULTS

top: CNOF/S bottom: SAMI3



GLOBAL VIEW OF TEC ($= \int n_e \, dr$)

'an infected cat scratch'



SAMI3/WACCM-X/HIAMCM MODELS

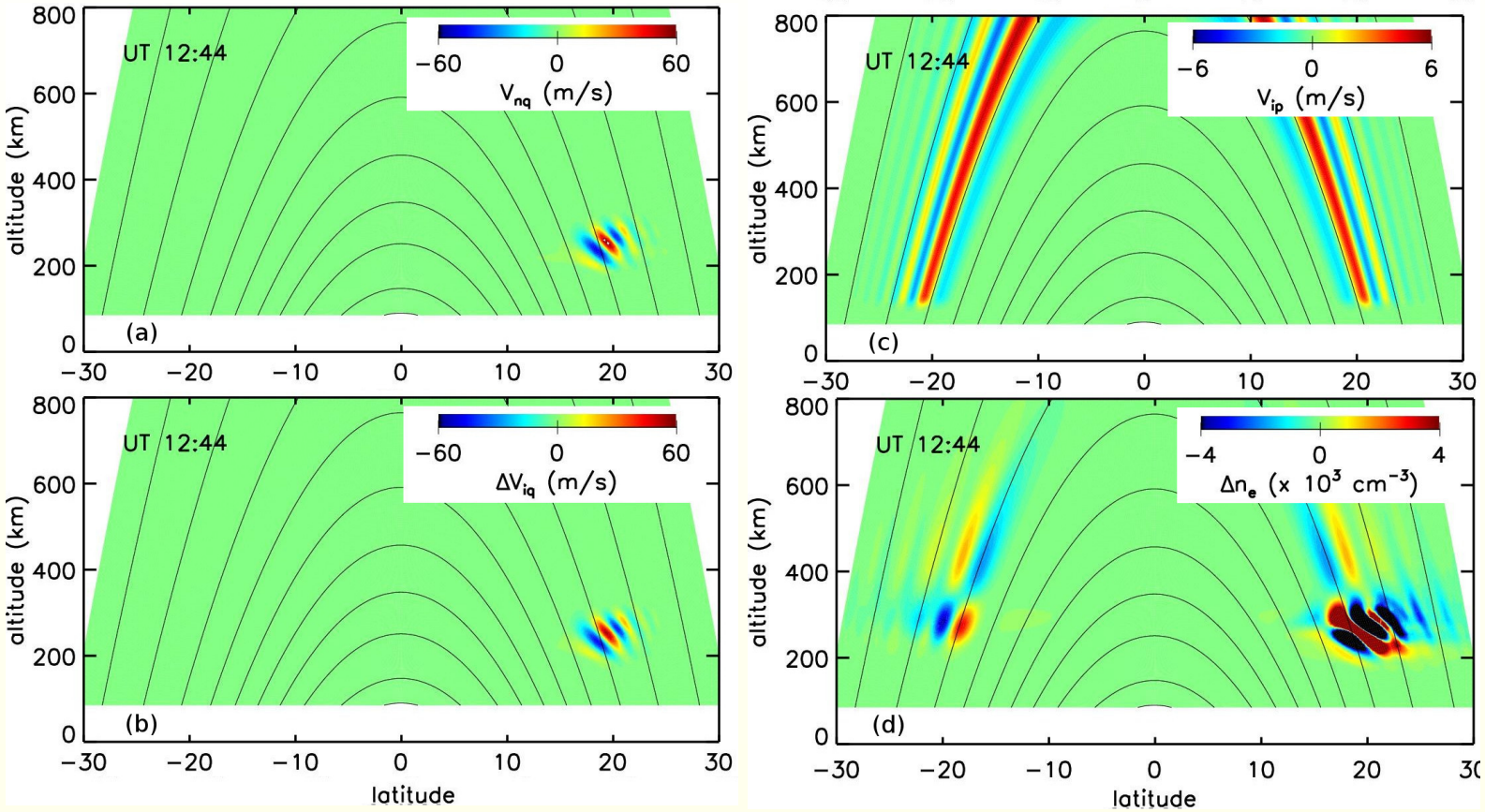
- SAMI3 (Huba et al., 2000; Huba and Joyce, GRL, 2010)
  - comprehensive, global ionosphere/plasmasphere model
  - ions modeled: H^+,O^+, He^+,N^+,N_2^+,NO^+,O_2^+
- WACCM-X (Liu et al., JGR, 2018)
  - WACCM is 'whole earth model' of the atmosphere
  - '-X' signifies model extended to 500 - 600 km
  - calculates neutral composition, temperature, winds
  - parameterizes gravity waves
- HIAMCM (Becker and Vadas, JGR, 2020)
  - high-resolution Khlungsborn Mechanistic general Circulation Model (KMCM) extended to z $\sim$ 450 km
  - explicitly simulates gravity waves (GWs) down to horizontal wavelengths $\sim$ 165 km

SAMI3/WACCM-X/HIAMCM MODELING

- codes are one-way coupled: thermospheric variables (e.g., winds) are inputs to SAMI3 but the SAMI3 ionosphere variables are not used in WACCM-X/HIAMCM
- spatial resolution
  - WACCM-X (NCAR): $\lesssim$ 70 km (lat: 0.474°; lon: .625°)
  - HIAMCM (NWRA): $\sim$ 50 km (lat/lon: .5°)
  - SAMI3:
    longitude same as WACCM-X/HIAMCM
    latitude is variable: 17 km (0.15° near the equator)
    to 170 km (1.5° at high latitude)
- highest resolution ionosphere/thermosphere runs to date
- SAMI3 uses 4th order flux-corrected transport algorithm (i.e., partial donor cell method) to reduce numerical diffusion

GRAVITY WAVE EFFECTS ON IONOSPHERE

wind perturbations; Huba et al., *GRL*, 2015

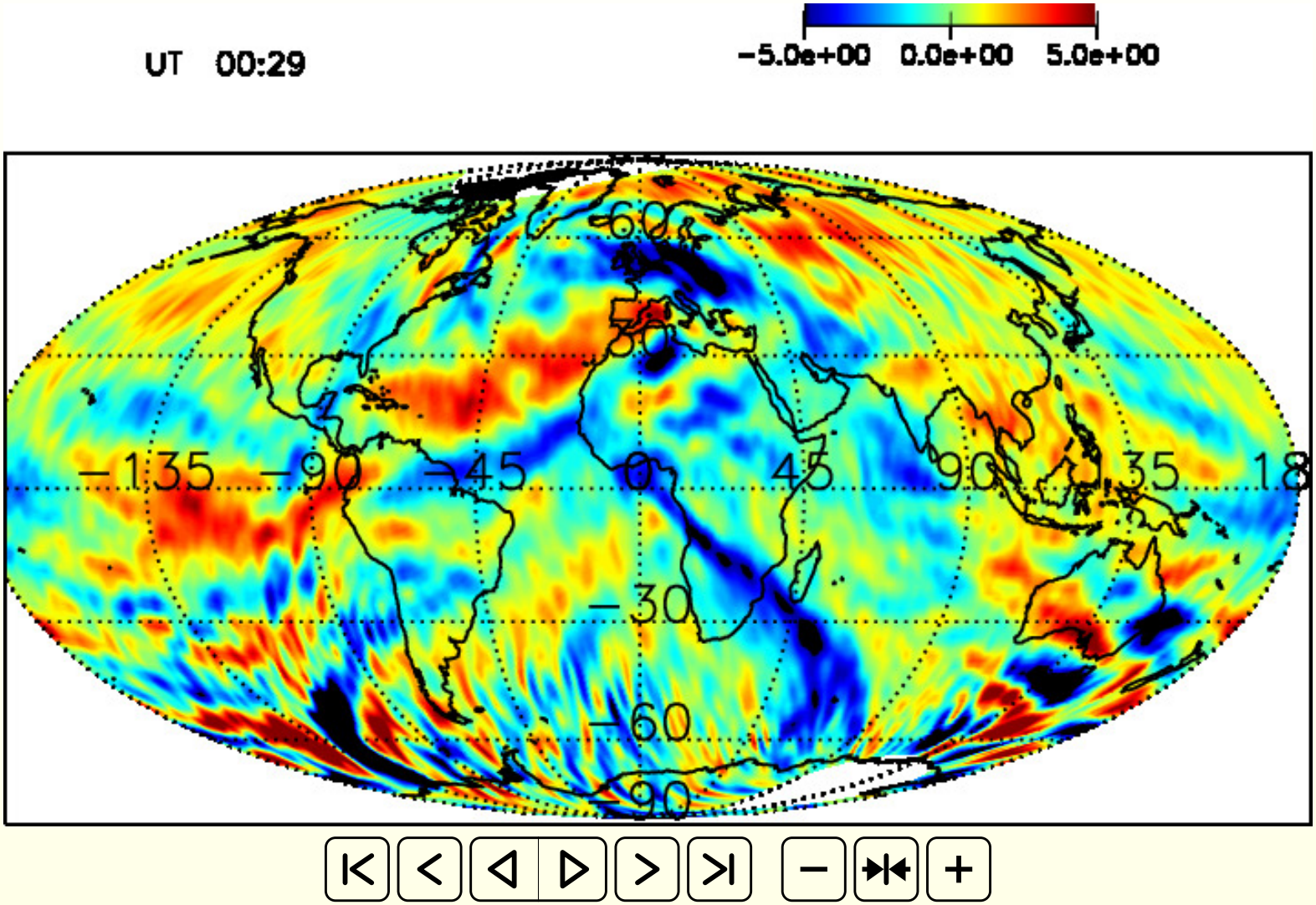


$$\frac{\partial \mathbf{V}_i}{\partial t} + \mathbf{V}_i \cdot \nabla \mathbf{V}_i = \frac{e}{m_i}\mathbf{E} - \nu_{in}(\mathbf{V}_i - \mathbf{V_n}) + \text{other terms}$$

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

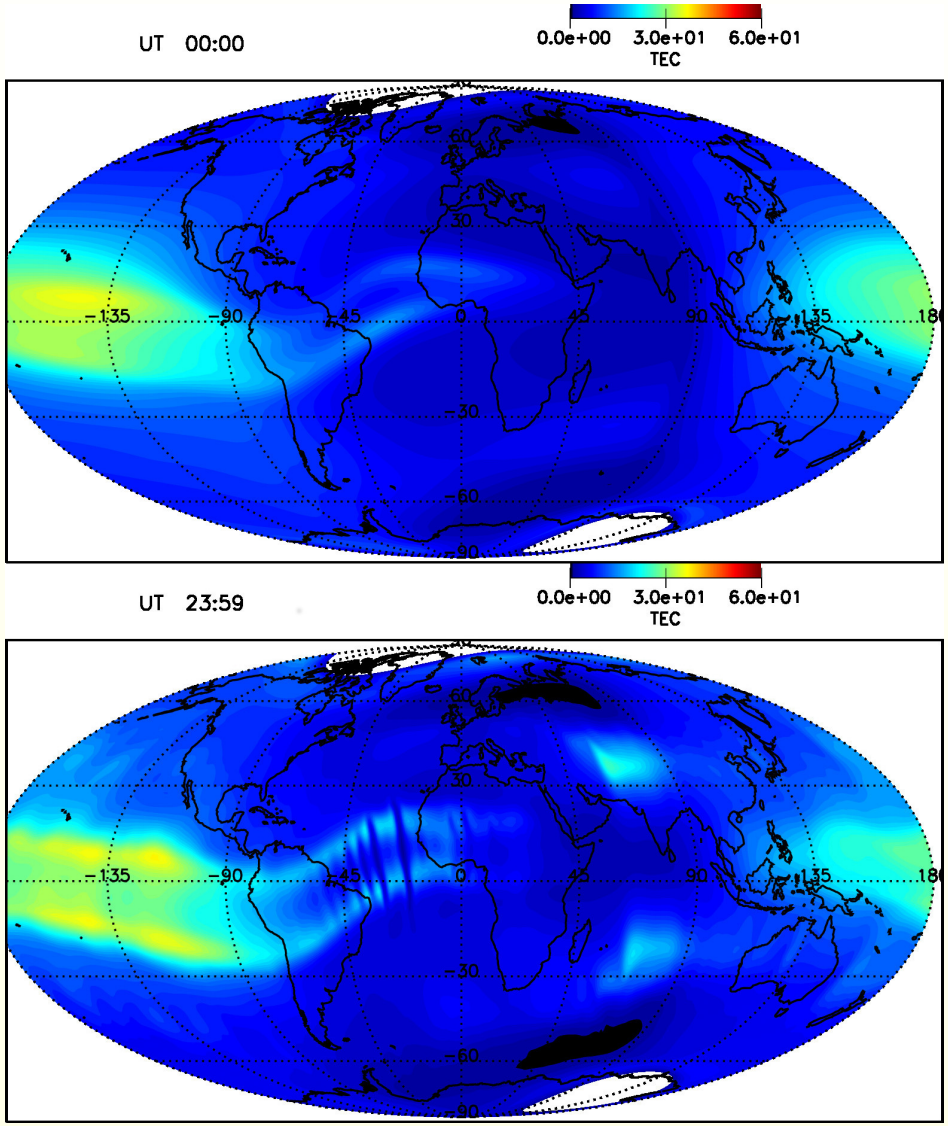
HIAMCM VERTICAL WIND

thermopshere spatial and temporal variability



SAMI3/WACCM-X: TEC

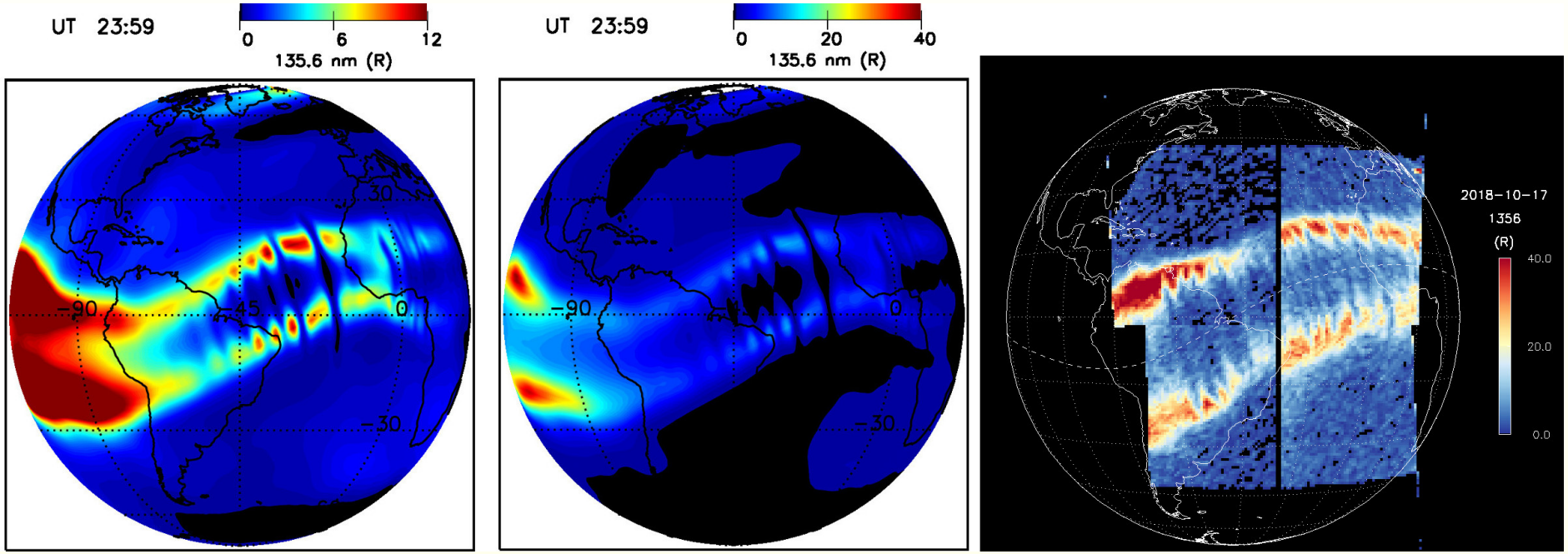
atmospheric waves 'seed' the instability



- total electron content (TEC)
  - march (F10.7 = 70)
- top: HWM14/NRLMSIS
  - plasma ESF bubbles do not form
- bottom: WACCM-X
  - plasma ESF bubbles form
  - longitudinally dependent
  - nighttime, mid-latitude ionosphere enhancements
    . plasmasphere 'drainage'
- Huba and Liu, *GRL*, 2020

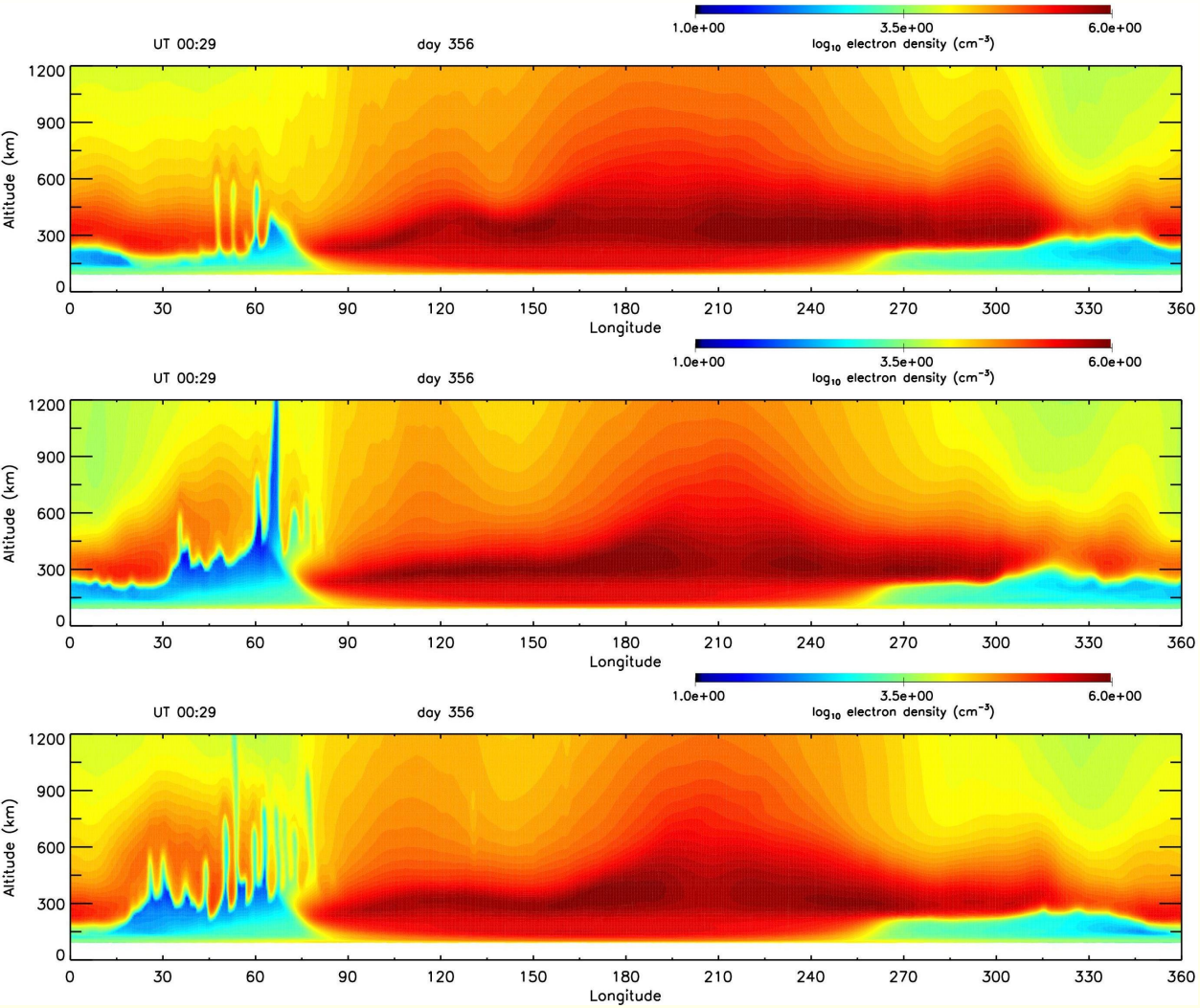
SAMI3/WACCM-X

comparison to GOLD 135.6 nm emissions (Eastes et al., *GRL*, 2019)



SAMI3/HIAMCM

jun 6/7/8, 2008 (low F10.7 = 70)



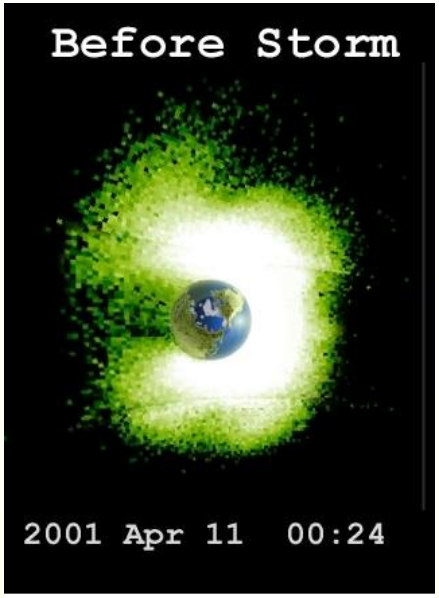
- electron density(log10) lon vs alt
- june 6 (top)
- june 7 (middle)
- june 8 (bottom)
- day-to-day and longitudinal variability

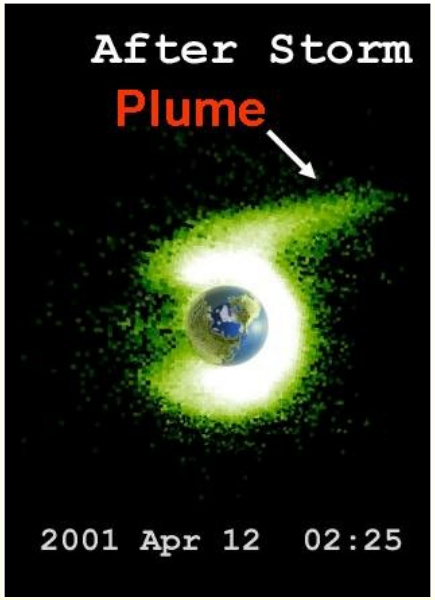
SUMMARY: IONOSPHERIC IRREGULARITIES

- performed highest resolution global ionosphere/plasmasphere simulation (SAMI3) using realistic thermospheric drivers (WACCM-X/HIAMCM) to date
- exciting new findings
  - onset and development of ESF plasma bubbles
  - atmospheric waves naturally provide 'seeds' for the instability
  - day-to-day and longitudinal variability
  - bubbles rising to very high altitudes ($>$ 1600 km)
  - post-midnight ESF and irregularities convecting into the morning sector
- future work
  - more simulations ... identify primary causes of day-to-day and longitudinal variability of ESF
  - more comparisons to GOLD/ICON data
  - use ICON neutral winds

NOW THE PLASMASPHERE

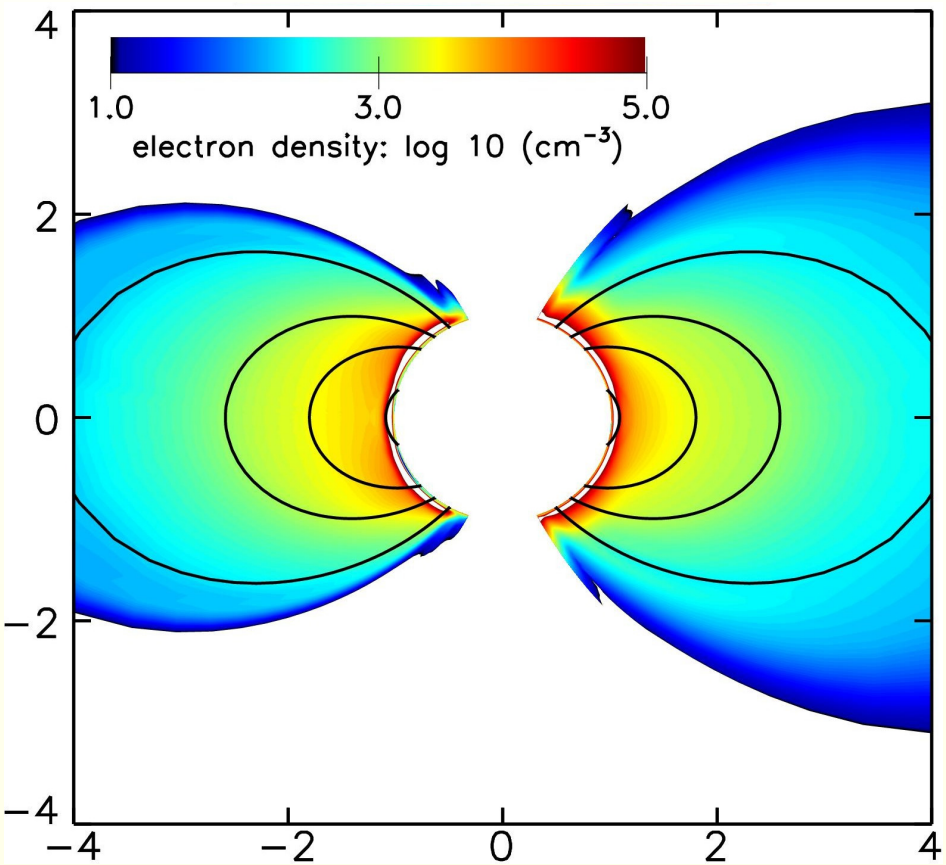
- extension of the ionosphere on closed field lines into the inner magnetosphere
- IMAGE data: He^+ (Goldstein ...)
- high density ($> 10^2$ cm^{-3})
  cold (T $\simeq$ few 1000 K) plasma
- ions: H^+ ($> 90\%$) and He^+
  (and a little O^+)
- range $2 < L < 7$
- collisionless
- storm-time erosion: hrs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

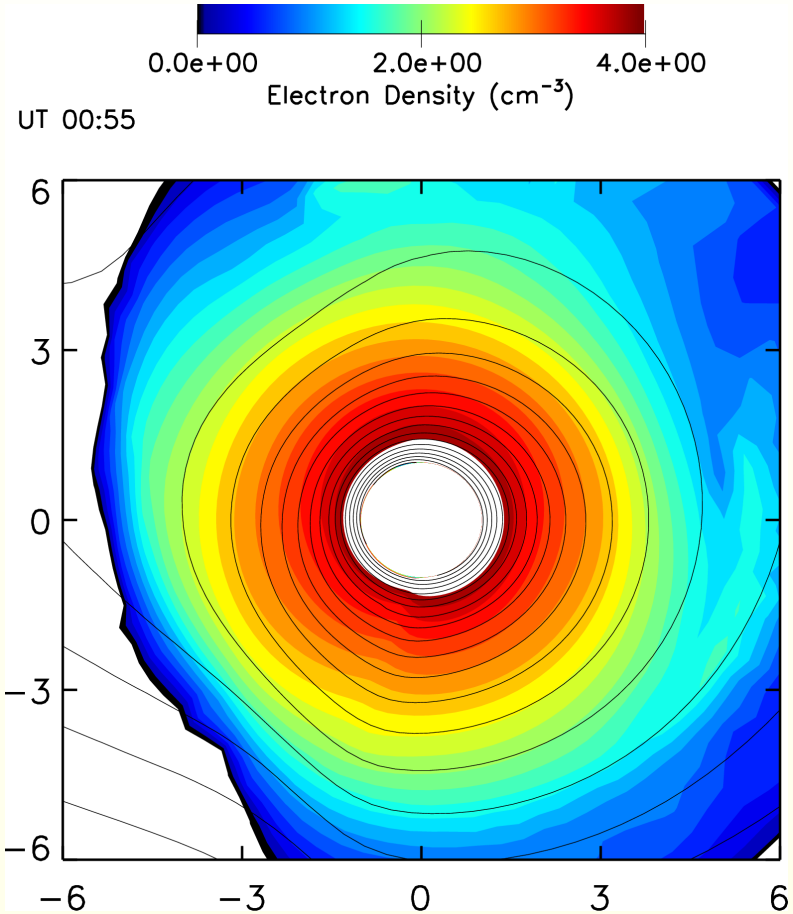




NOMINAL RESULTS

from SAMI3: meridional and equatorial planes





EMAIL FROM MY BROTHER

Re: Real or Crap?

Joe Huba <jdhuba@gmail.com>
to John

Thu, Jun 4, 2015, 1:52 PM

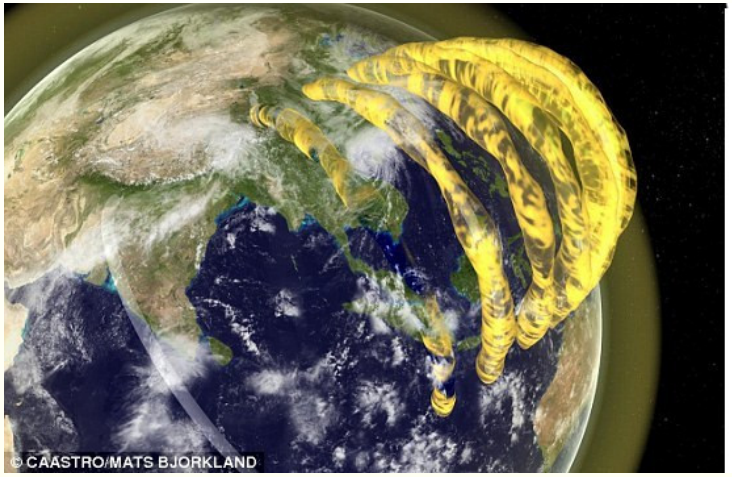
On Jun 4, 2015 8:36 AM, "John Huba" <info@johnhuba.com> wrote:

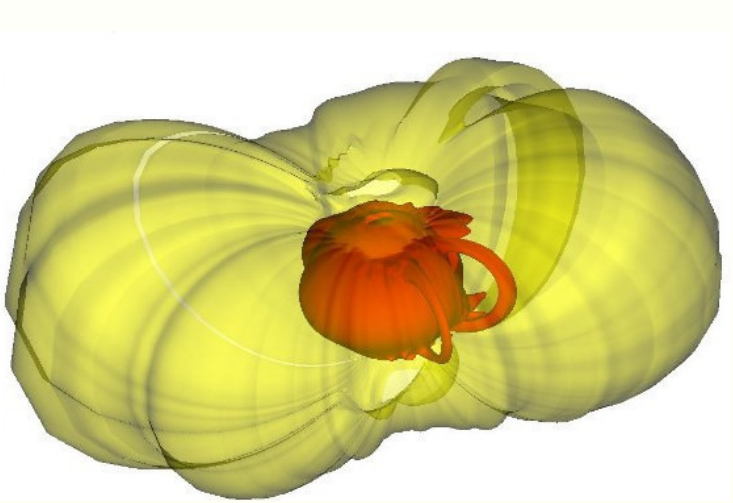
> http://www.sciencealert.com/australian-student-confirms-that-giant-plasma-tubes-are-floating-above-earth
>
> HUBA
>
> info@johnhuba.com
> johnhubastudio.com
> johnhubafilm.com

AND CLICKING ON THE LINK ...

PLASMASPHERE DUCTS/IRREGULARITIES

intriguing comparison to data

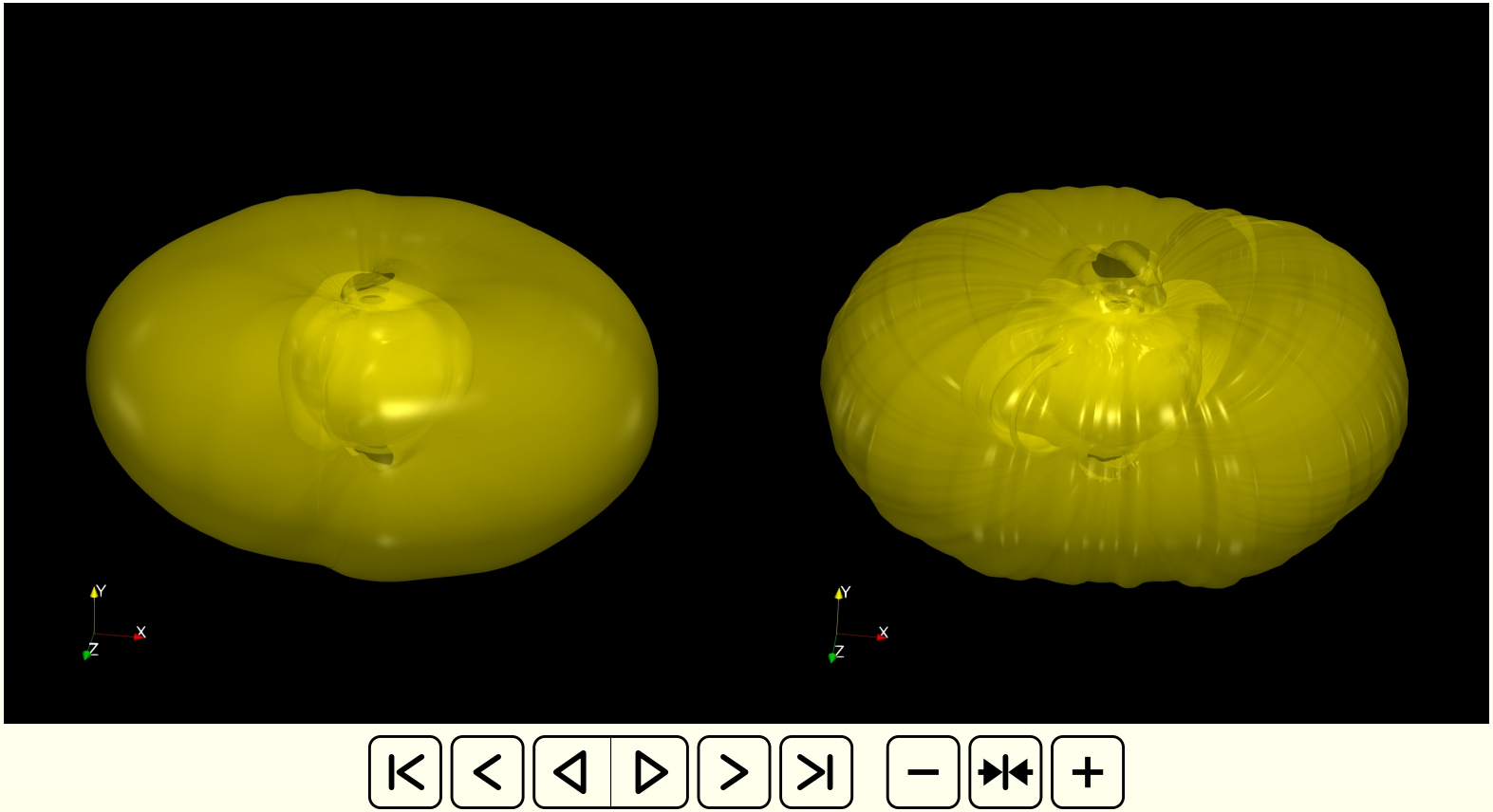




- ducts observed from the MWA facility in Australia by Loi et al. (2015) (top left)
- SAMI3/HIAMCM (top right)
- other observations of plasmasphere ducts
  - Jacobson and Erickson (1993)
  - Helmboldt et al. (2020)

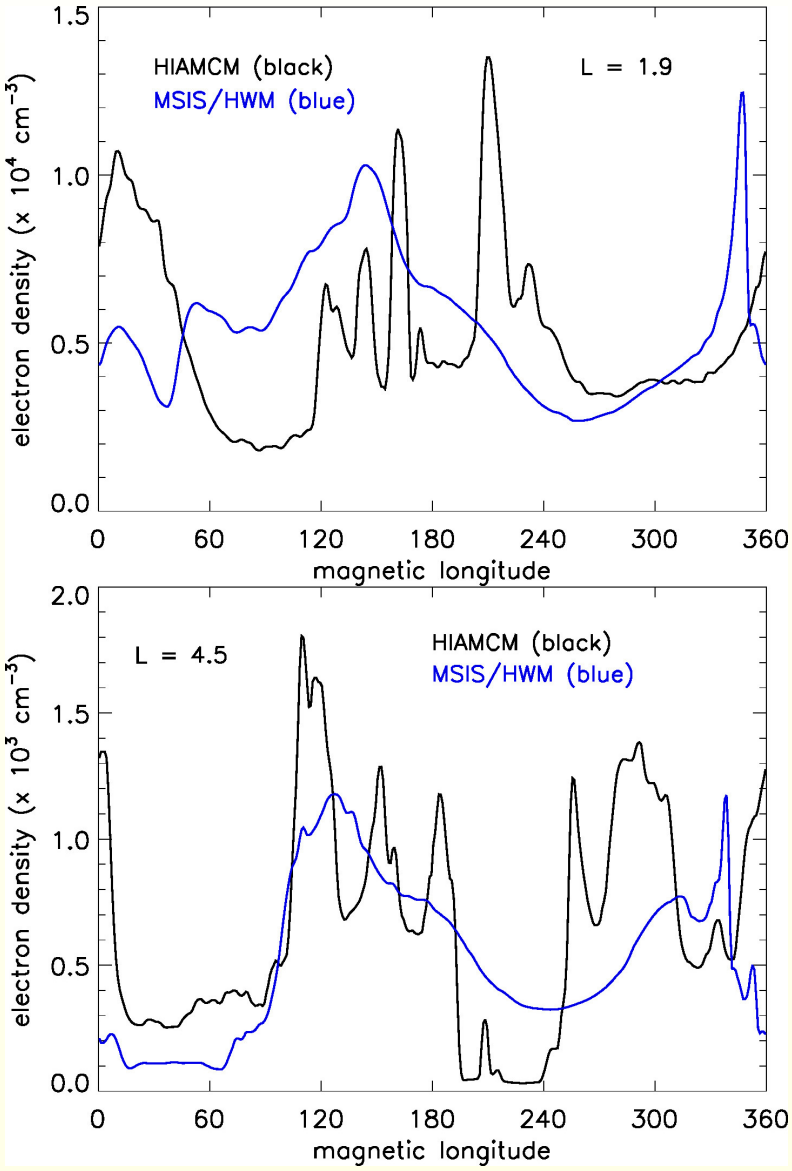
IONOSPHERE/PLASMASPHERE STRUCTURE

SAMI3/MSIS/HWM/ and SAMI3/WACCM-X



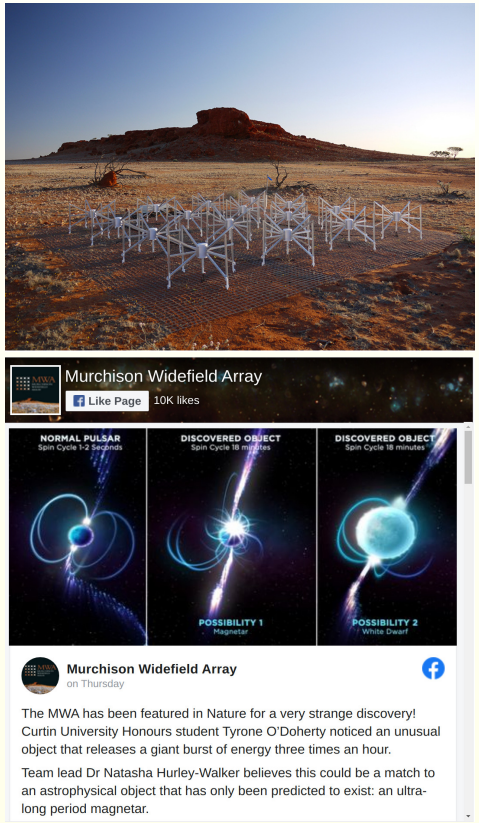
- left: MSIS/HWM (boring) right: WACCM-X (not boring)

ELECTRON DENSITY VS LONGITUDE



- compare HIAMCM (black) vs MSIS/HWM (blue)
- as a function of L shell and longitude
- irregularities with variations: $\lesssim$ factor of 2

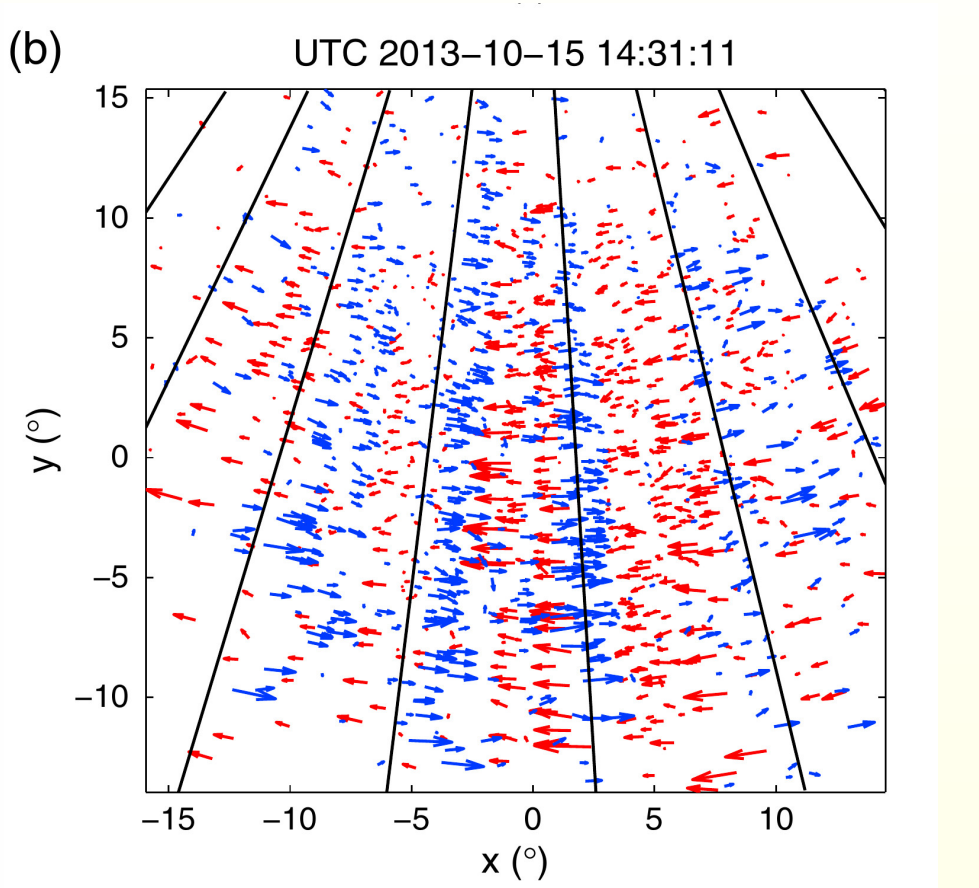
MURCHISON WIDE FIELD ARRAY



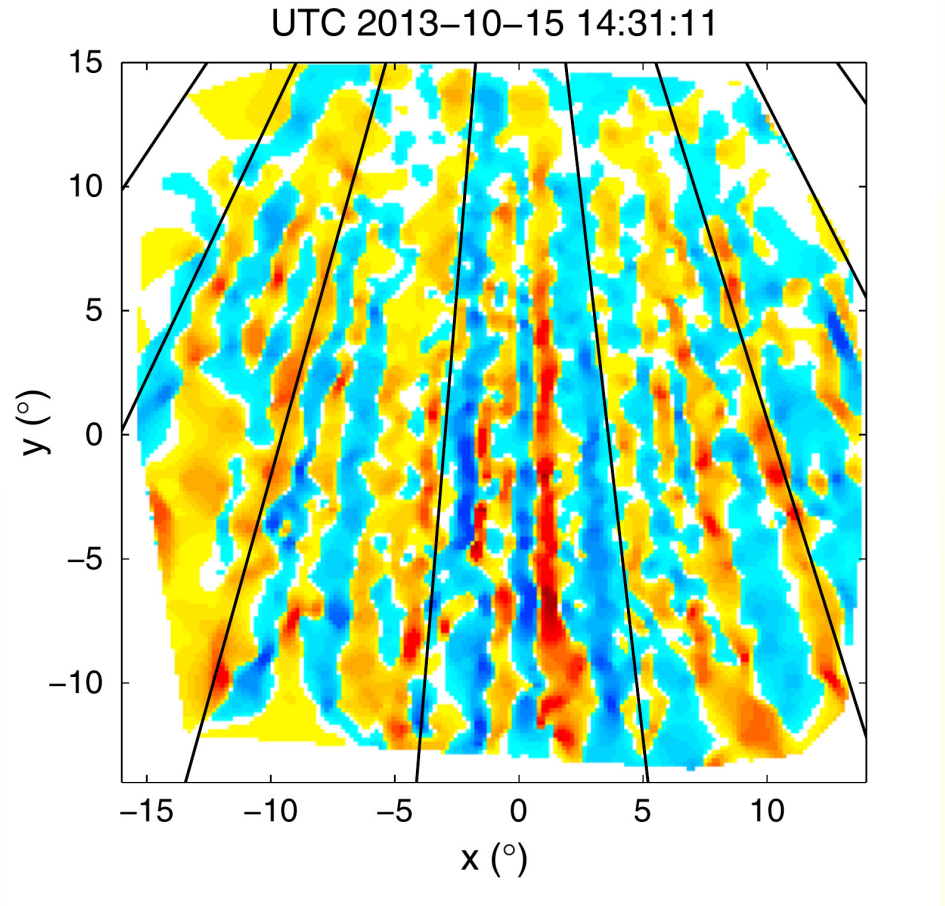
- a low-frequency radio telescope in Western Australia
- front-end of the MWA consists of 4,096 spider-like antennas arranged in 256 regular grids called tiles
- spread over several kilometres
- nominally designed to study astrophysical objects
- but can detect ionospheric disturbances on scales of ~ 1 s and ~ 1 km

MURCHISON WIDE FIELD ARRAY

from Loi et al., GRL, 2015



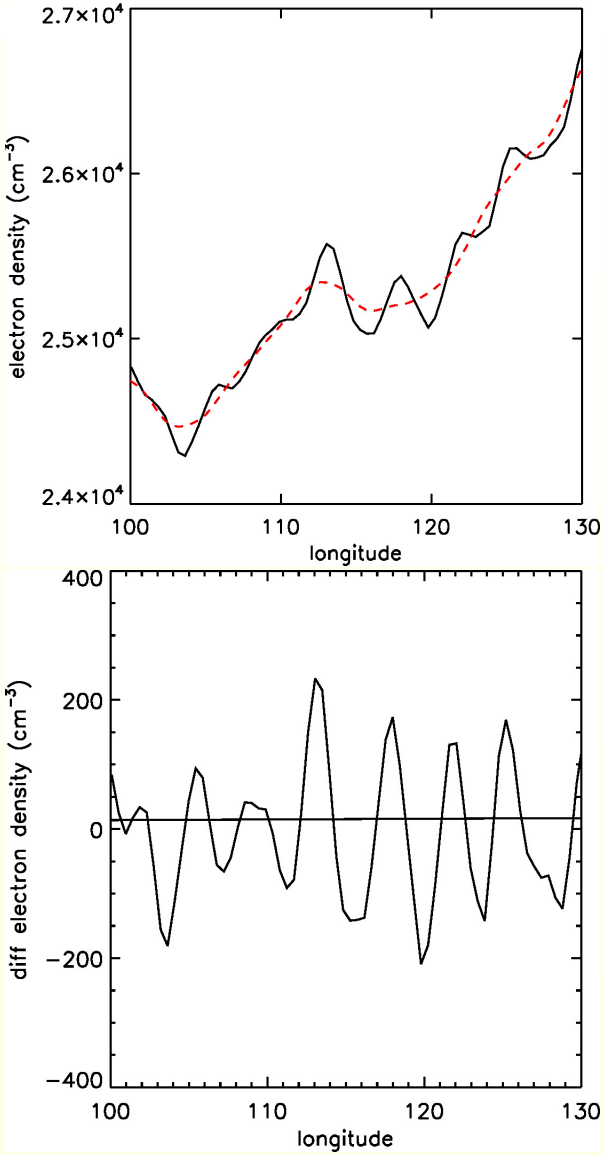
velocities



divergence of velocities

DENSITY VS LONGITUDE

SAMI3/HIAMCM (06/06/2008)



- 14:30 UT but different day/year
- at murchison (lat = -26° and alt = 600 km)
- top: electron density actual (black) and smoothed (red)
- bottom: electron density difference (black-red)
- number of peaks/valleys similar to Loi et al. (2015)

VERY LARGE ARRAY

national radio astronomy observatory

- centimeter-wavelength radio telescope in Socorro, NM
- comprises twenty-eight 25-meter radio telescopes
- nominally designed to study astrophysical objects
- but can detect ionospheric disturbances on scales of ~ 1 s and ~ 1 km

COROTATING PLASMASPHERIC IRREGULARITIES

Helmboldt et al., JGR, 2020

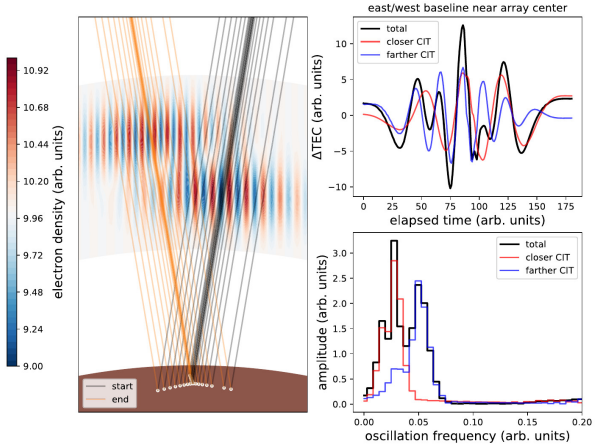
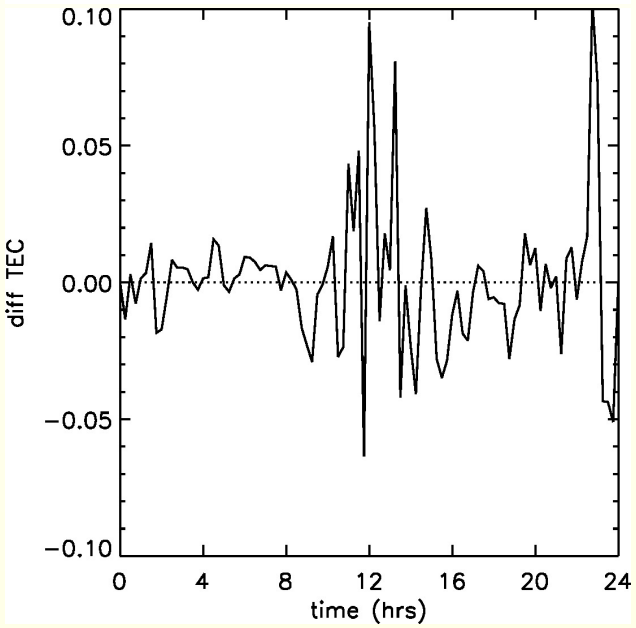


Figure 1. A schematic (not to scale) of a VLA observation of two CPIs. The ΔTEC between the lines of sight of two antennas near the center of the array are shown in the upper right panel. The total ΔTEC is shown in black, while the values for the individual CPIs are in red and blue. The bottom right panel shows the amplitudes of the Fourier transforms of the time series plotted in the upper right panel.



- top: schematic of VLA observation of two CPIs
- top (top right): total ΔTEC vs time in black while individual ΔTECs in red and blue
- bottom: SAMI3/HIAMCM ΔTEC vs time over Socorro, NM
- both figures show temporal variation of ΔTEC
- but not necessarily on same time/length scales
- need further work to resolve differences

IONOSPHERE/PLASMASPHERE DUCTING

- calculate 'TEC' along a flux tube

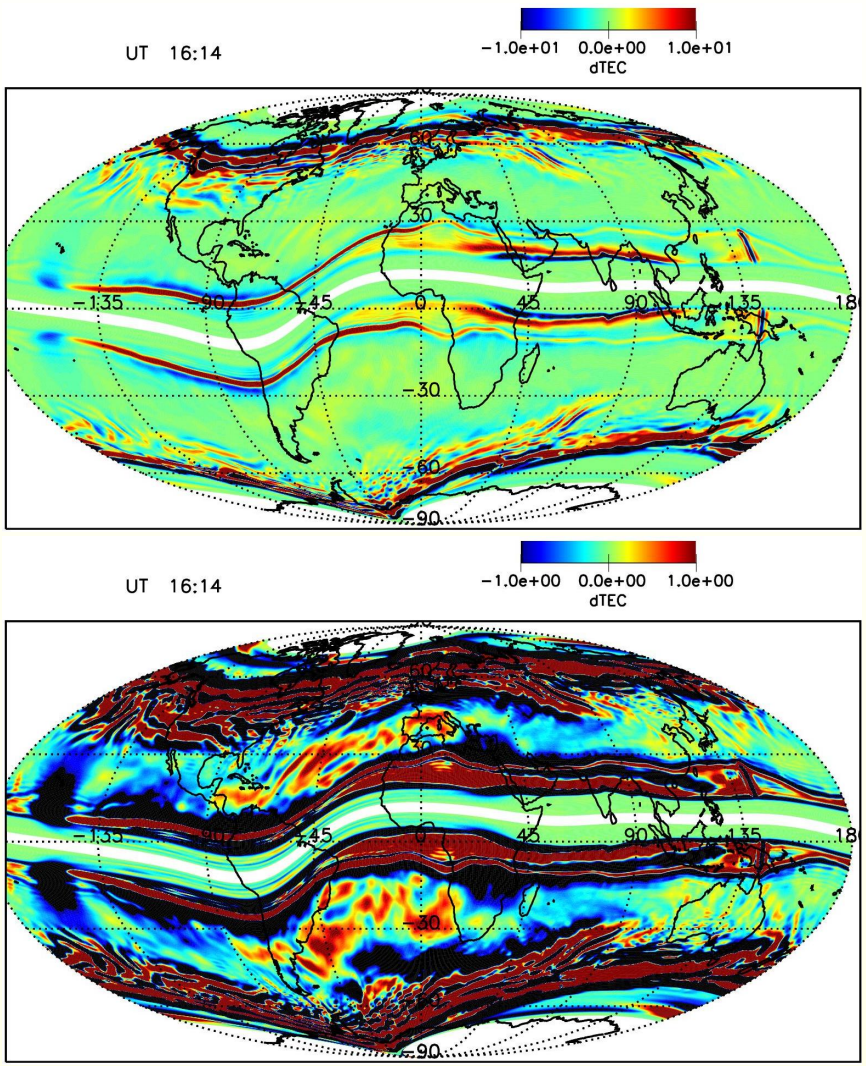
$$\mathrm{TEC}_{flux\ tube} = \int n_e \frac{B_0}{B}\, ds$$

  here ds is along the magnetic field line

- plot dTEC = TEC$_{flux\ tube}$ - smoothed(TEC$_{flux\ tube}$) to highlight ducts

IONOSPHERE/PLASMASPHERE DUCTING

SAMI3/WACCMX



- 21 march 2008 (F10.7 $\sim$ 70)
- top: dTEC $= \pm 10$ TECU
- bottom: dTEC $= \pm 1$ TECU

SUMMARY: PLASMASPHERE STRUCTURE

- plasma ducting and corrugations in the plasmasphere
- first time observed in a global ionosphere/thermosphere model
- suggets atmospheric waves influence plasma dynamics in the inner magnetosphere
- future work
  - identify underlying physics leading to ducting
  - compare to data (density and electron temperature)
  - relate to VLF/whistler wave studies

SOME FINAL COMMENTS

- the sami3/waccmx simulations showing the onset and nonlinear development of equatorial plasma bubbles was a complete surprise
- was anticipating low level ionospheric waves such as traveling ionospheric disturbances
- the resemblance of the 134.6 emissions from the model in the Atlantic sector to GOLD data was even more surprising
- and lastly, plasmasphere structure and ducts were also a surprise
- (hope i haven't used up my quota of scientific surprises)

- ion continuity

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

- ion velocity (includes ion inertia)

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

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

- electron momentum

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

POTENTIAL EQUATION

based on current conservation: $\nabla \cdot \mathbf{J} = 0$

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

$$\frac{\partial}{\partial p} \Sigma_{pp} \frac{\partial \Phi}{\partial p} + \frac{\partial}{\partial \phi} \Sigma_{p\phi} \frac{\partial \Phi}{\partial \phi} = \underbrace{\frac{\partial F_{\phi g}}{\partial \phi}}_{\text{driver}} + \underbrace{\frac{\partial F_{\phi V}}{\partial \phi}}_{\text{meridional}} + \underbrace{\frac{\partial F_{pV}}{\partial p}}_{\text{zonal}}$$

driver:

$$F_{\phi g} = \int \frac{r_0 \sin^3 \theta}{\Delta} \frac{B_0}{c} \frac{1}{\Omega_i} \sigma_{Hi} g_p ds$$

meridional wind:

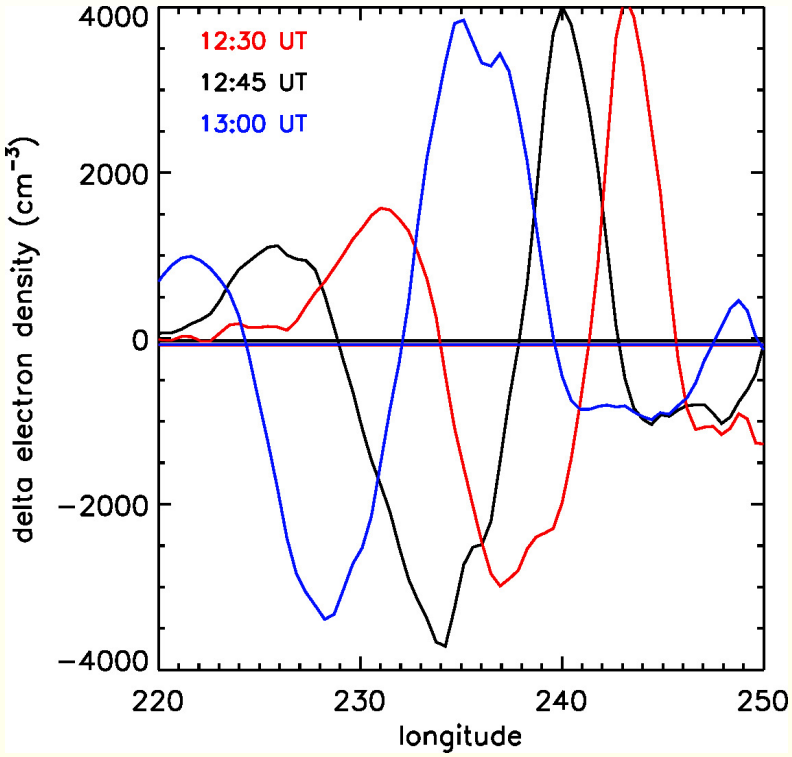
$$F_{\phi V} = -\int \frac{B_0}{c} \frac{r_0 \sin^3 \theta}{\Delta} \sigma_P V_{np} ds$$

zonal wind:

$$F_{pV} = \int \frac{B_0}{c} r \sin \theta \sigma_P V_{n\phi} ds$$

COROTATING PLASMASPHERIC IRREGULARITIES

model results



- SAMI3 has sun revolving around the earth (Ptolemian)
- so corotating structures move overhead, i.e., not stationary as in corotaing frame
- Δn_e at three times
- 12:30 UT / 12:45 UT / 13:00 UT
- drift velocity $\sim$ 400 - 500 m/s
- a bit faster than corotation velocity at 34° of $\sim$ 382 m/s but there is also a westward plasma drift $\sim$ 50 m/s