Three-dimensional high-resolution plasma bubble modeling

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Equatorial Spread F

Spread F – an old equatorial aeronomy problem finally resolved?

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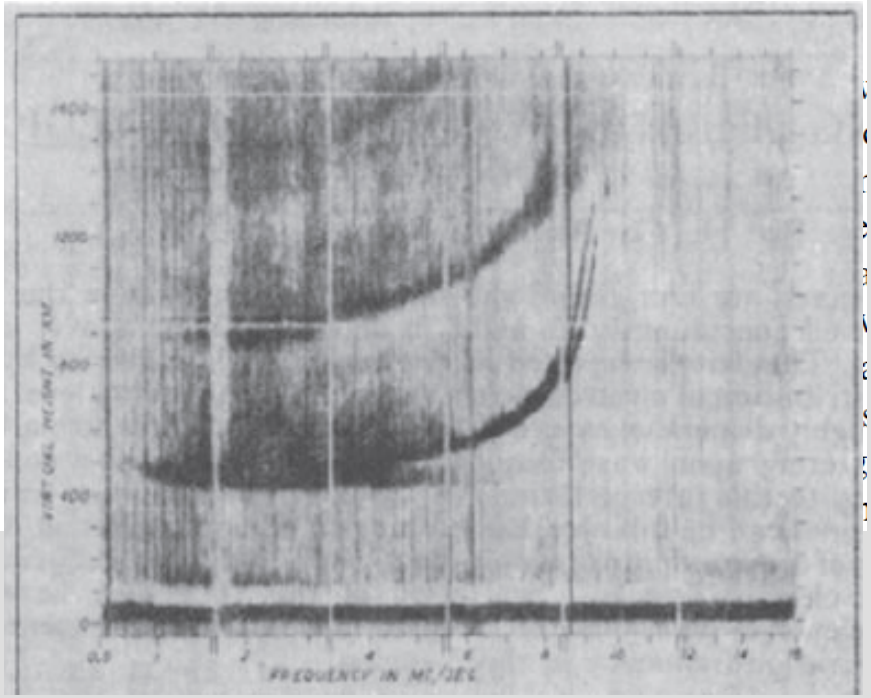
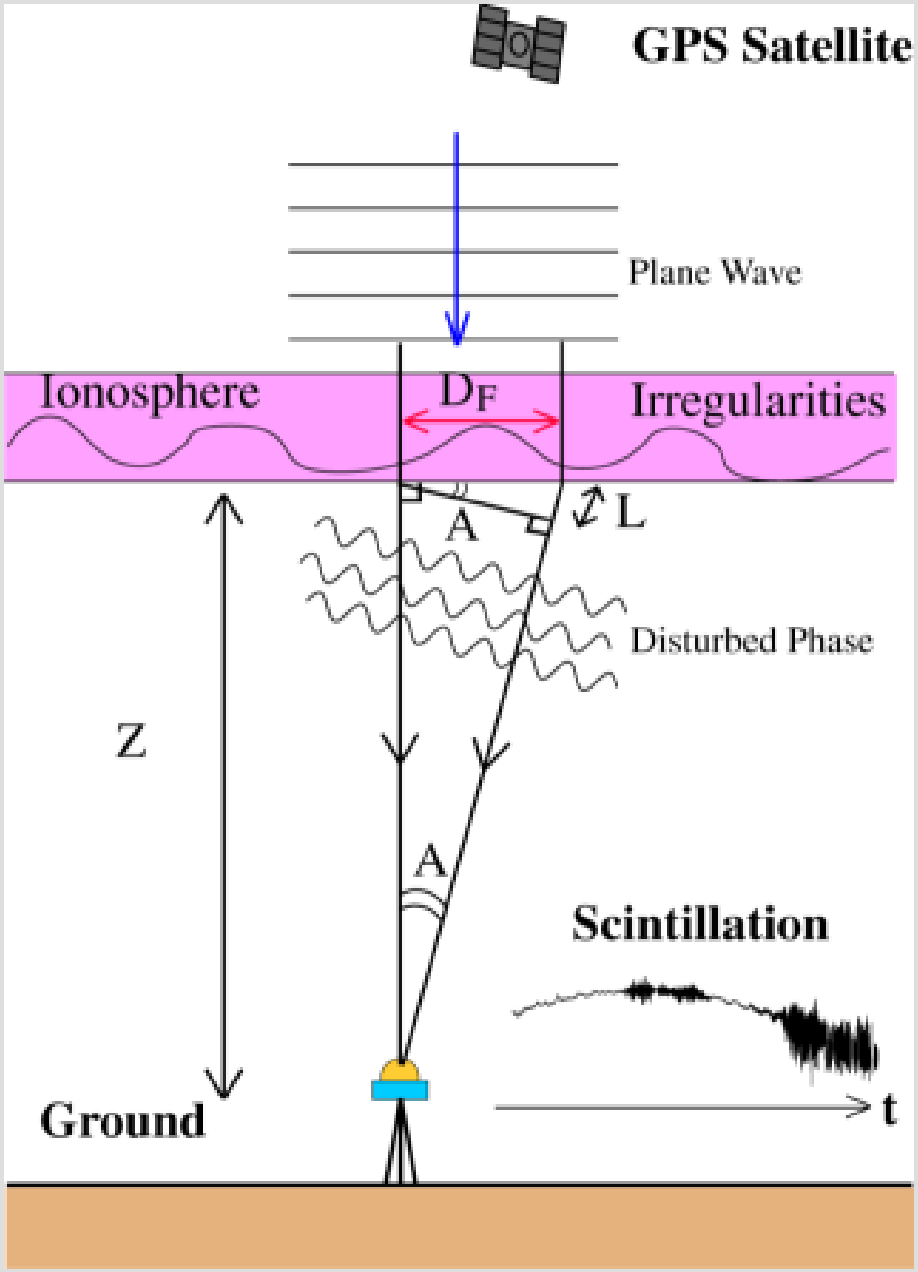
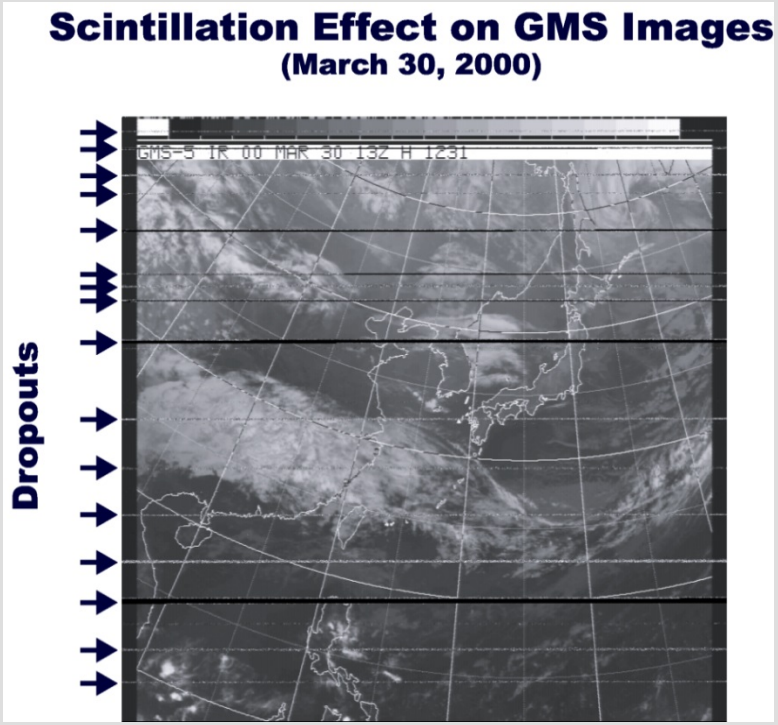
Abstract. One of the oldest scientific topics in Equatorial Aeronomy is related to Spread-F. It includes all our efforts to understand the physical mechanisms responsible for the existence of ionospheric F-region irregularities, the spread of the traces in a night-time equatorial ionogram – hence its name – and all other manifestations of the same. It was observed for the first time as an abnormal ionogram in Huancayo, about 70 years ago. But only recently are we coming to understand the physical mechanisms responsible for its occurrence and its capricious day to day variability. Several ad-



Booker and Wells (1938)

Scintillation

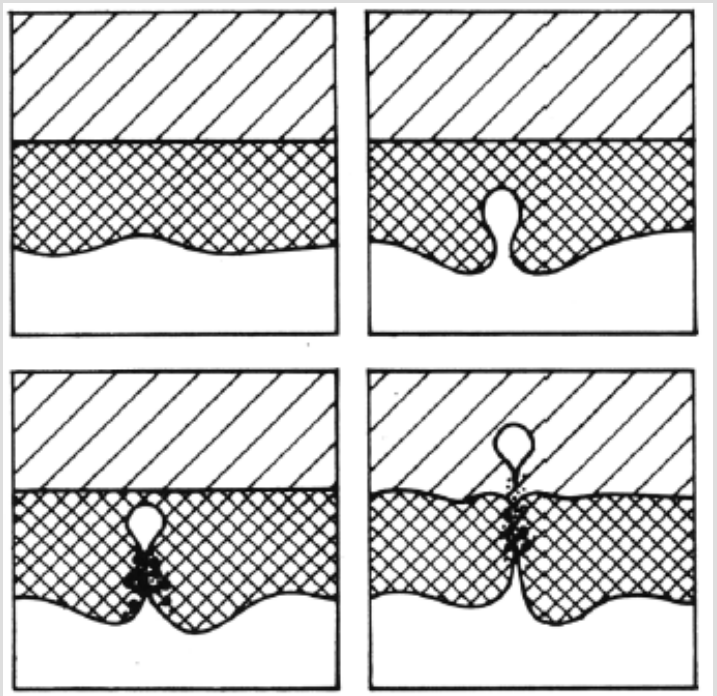


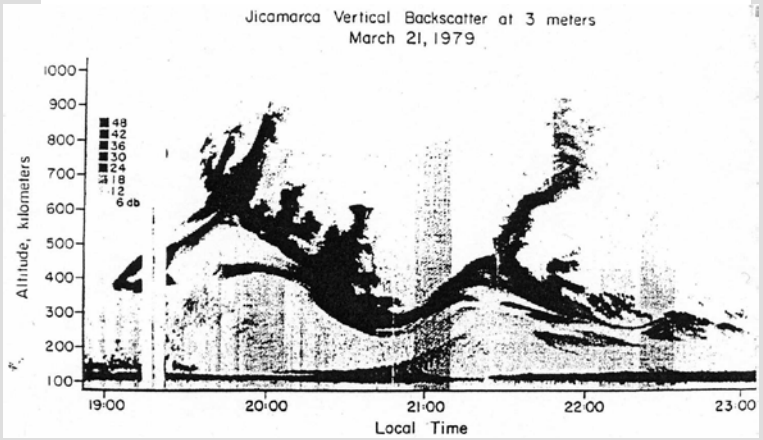


- Fresnel diffraction
  $\sqrt{2}D_F = \sqrt{2\lambda z} \approx 400\text{m}$
- Serious problem for communication and navigation.

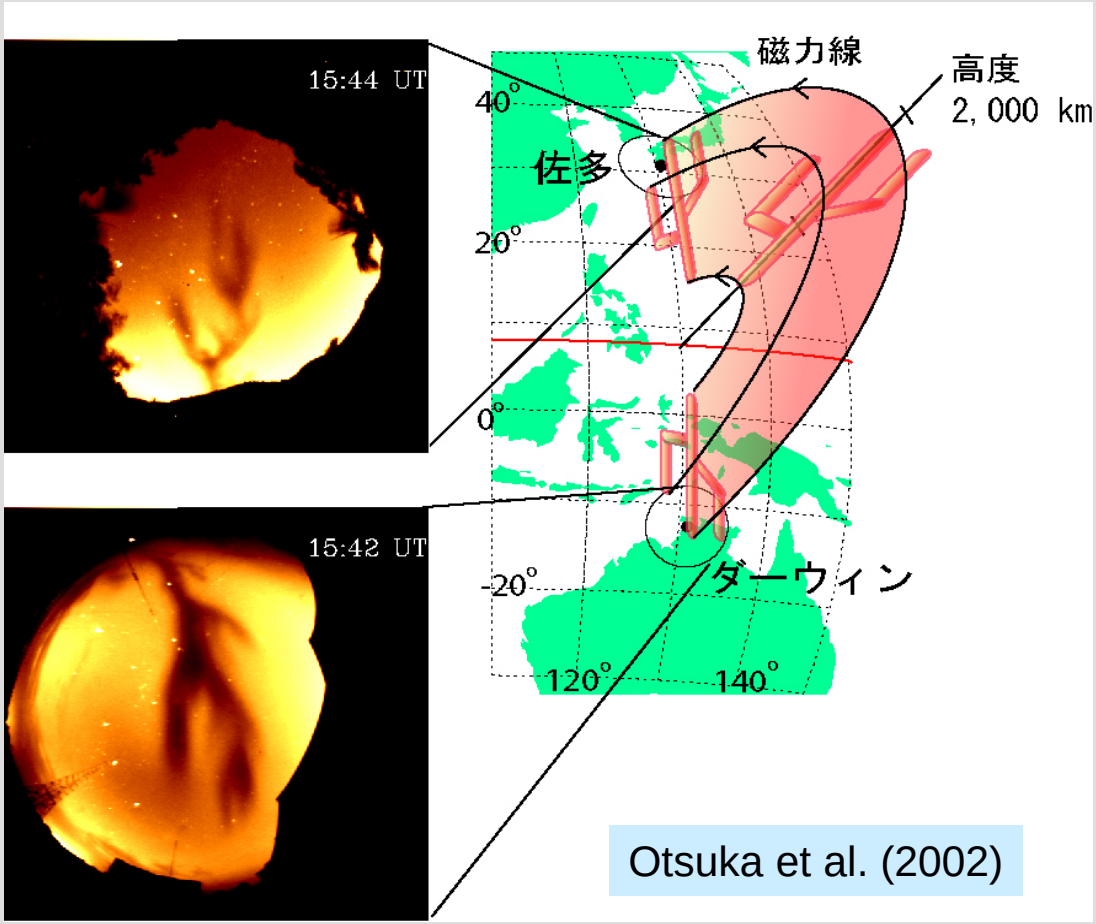
Plasma Bubble

Woodman and LaHoz (1976)





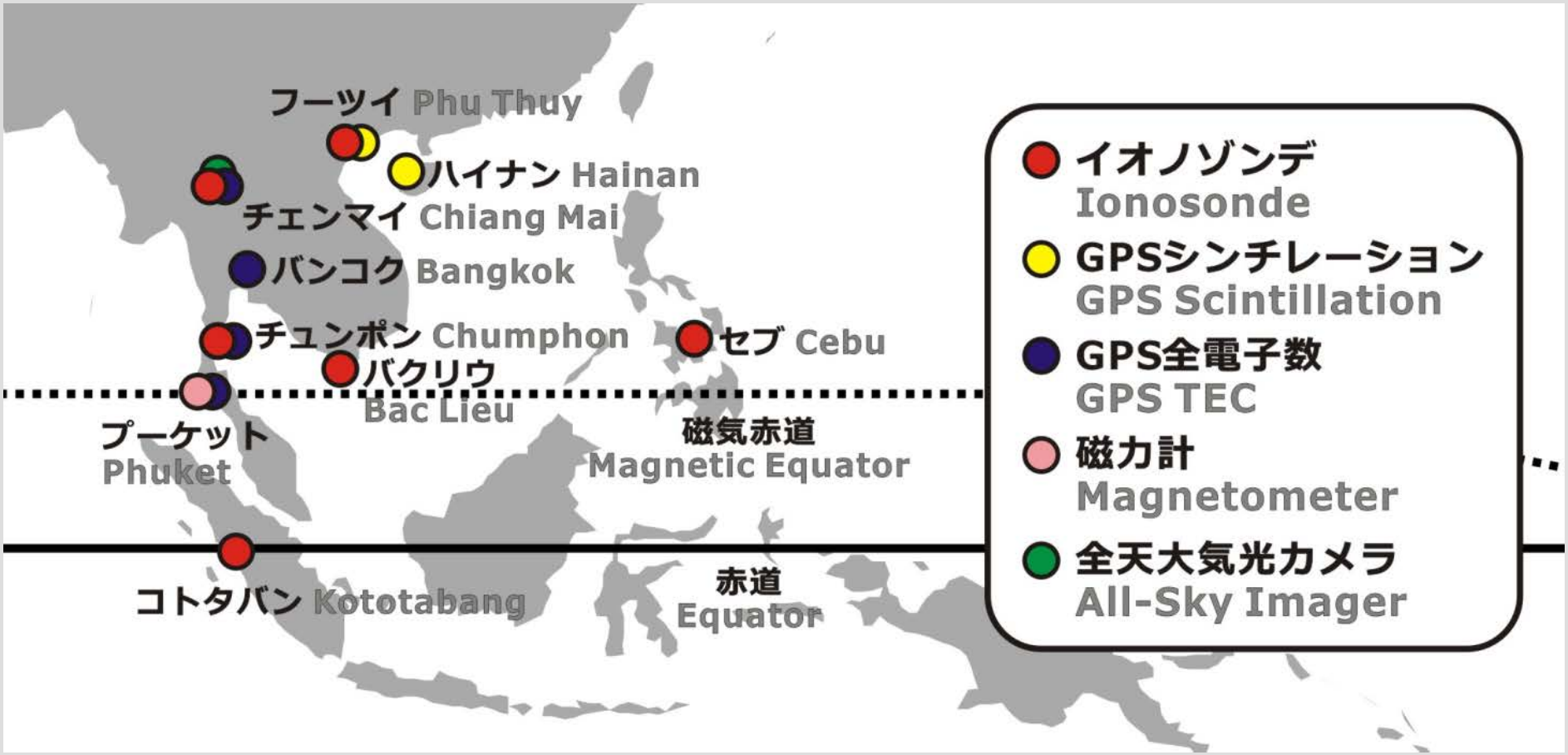
Kelley et al. (1981)



Otsuka et al. (2002)

- 99% density depletion causes severe scintillation.

NICT's SEALION Observatories



Numerical Modeling of Plasma Bubbles

- What we have not known:
  - Day-to-day variability
  - Precursor
- We need to understand:
  - Background conditions to drive plasma bubble
  - Initial seeding at the bottomside F region
- Various observations (radars, optical imagers, rockets, satellites) have been conducted, but not answered yet (for more than 70 years!)
- We are developing a new high-resolution model and integrating it to a global ionosphere model.

Equations

$$\frac{\partial N_i}{\partial t} + \nabla \cdot (N_i \mathbf{V}_i) = S_i \tag{1}$$

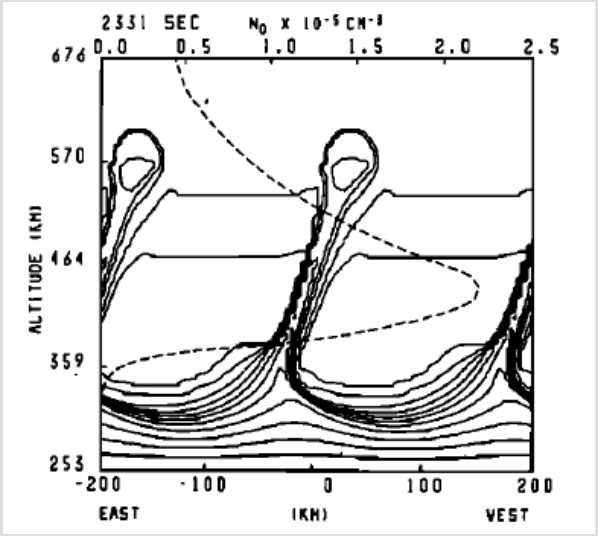
$$e(\mathbf{E} + \mathbf{V}_i \times \mathbf{B}) + M_i \boldsymbol{g} - \frac{\nabla(N_i k_B T)}{N_i} + M_i \nu_{in}(\mathbf{U} - \mathbf{V}_i) = 0 \tag{2}$$

$$-e(\mathbf{E} + \mathbf{V}_e \times \mathbf{B}) + M_e \boldsymbol{g} - \frac{\nabla(N_e k_B T)}{N_e} + M_e \nu_{en}(\mathbf{U} - \mathbf{V}_e) = 0 \tag{3}$$

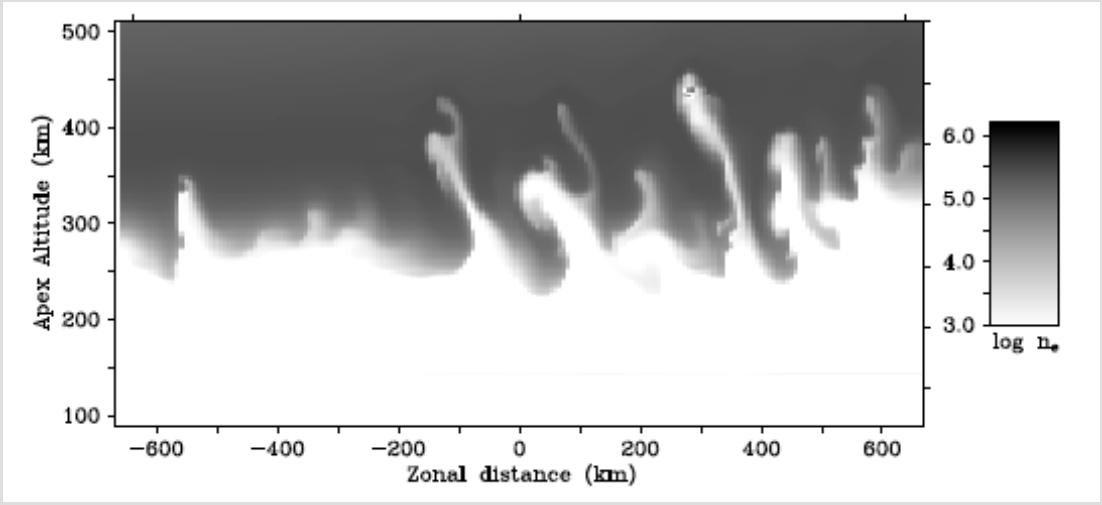
$$\nabla \cdot \mathbf{J} = \nabla \cdot \left[e \left(\sum_i N_i \mathbf{V}_i - N_e \mathbf{V}_e \right) \right] = 0 \tag{4}$$

- Plasma density is solved from (1).
- Polarization electrostatic potential is solved from (2)-(4).

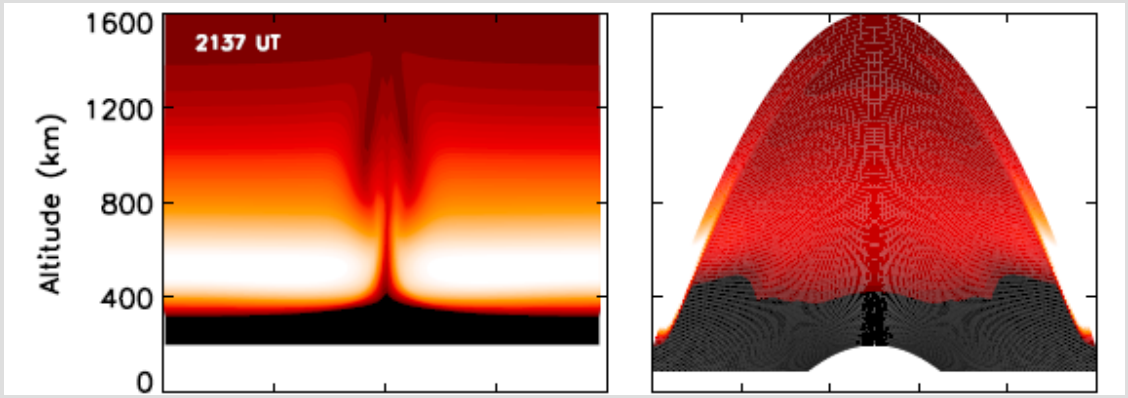
Other Models



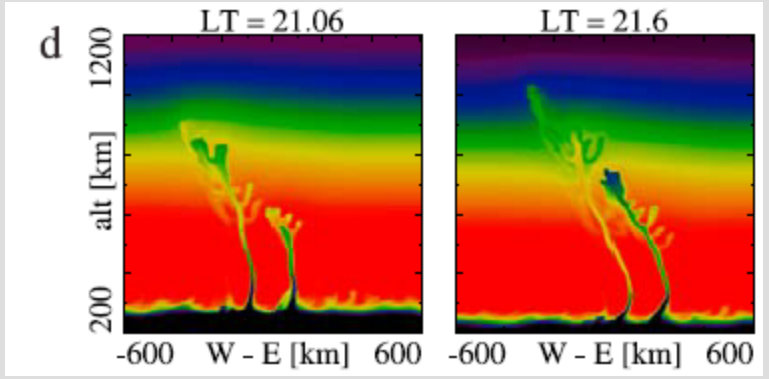
Zalesak et al. (1982)



Aveiro et al. (2012)

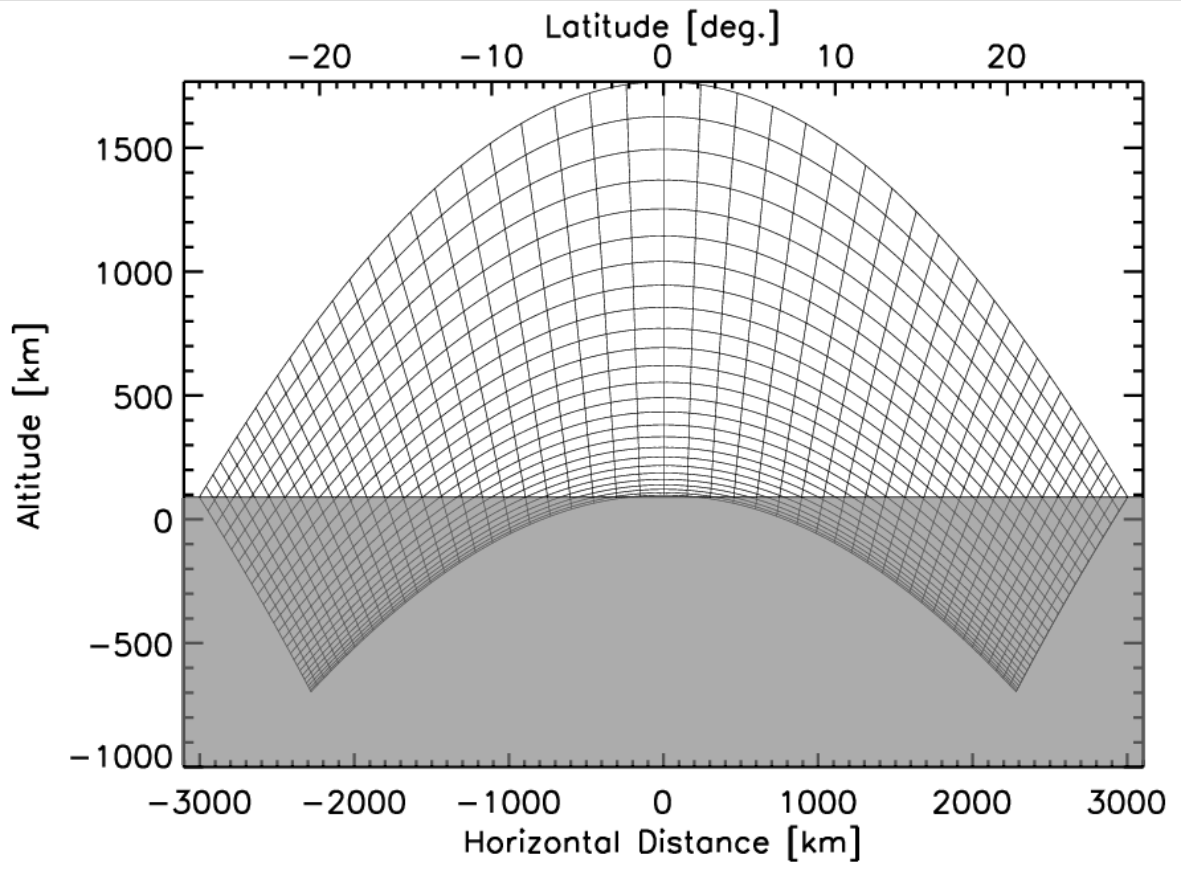


Huba et al. (2008)



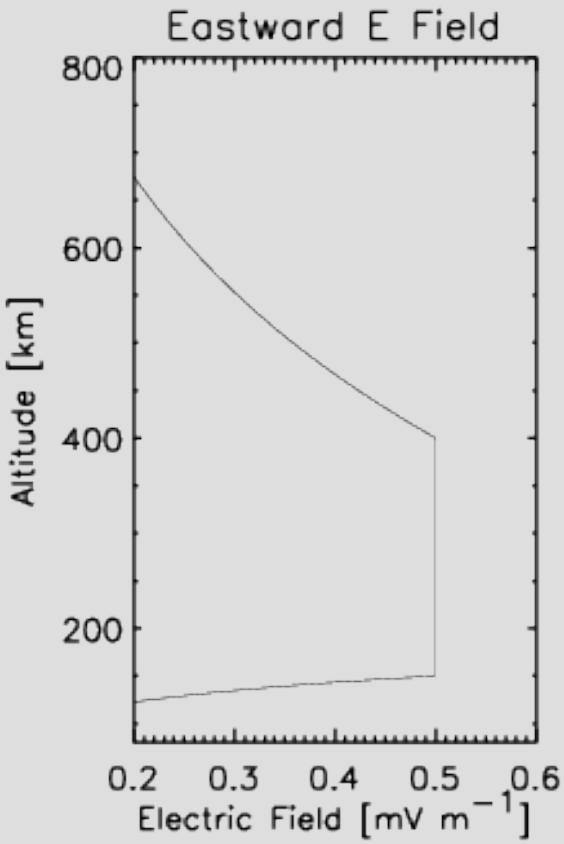
Retterer (2010)

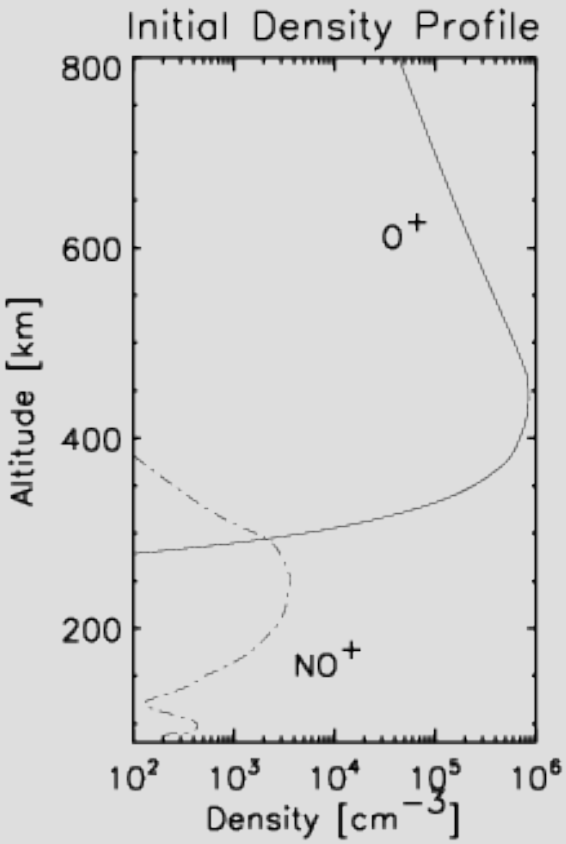
Numerical Model for Plasma Bubble

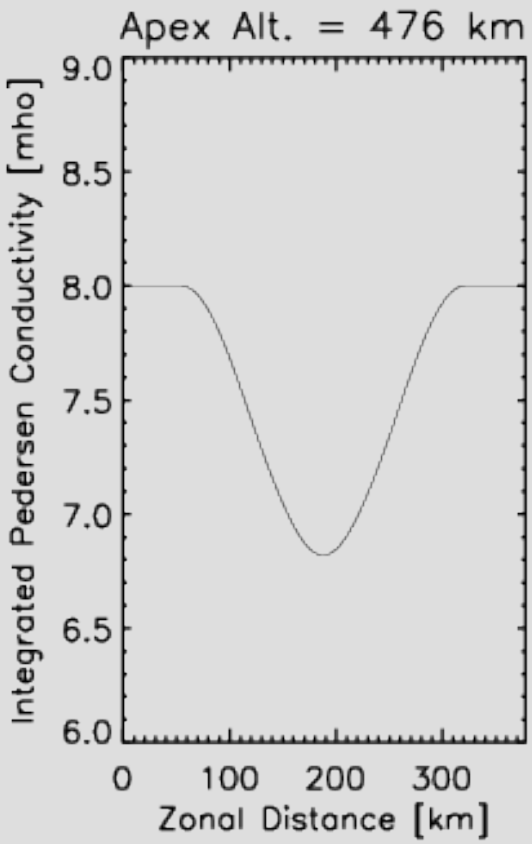


- Dipole orthogonal coordinate
- Longitudinal coverage is 3.4° with 0.01° resolution (~1km).
- O^+ (F region), NO^+ (E region), Fe^+ (Es layer [not yet])

Initial Condition

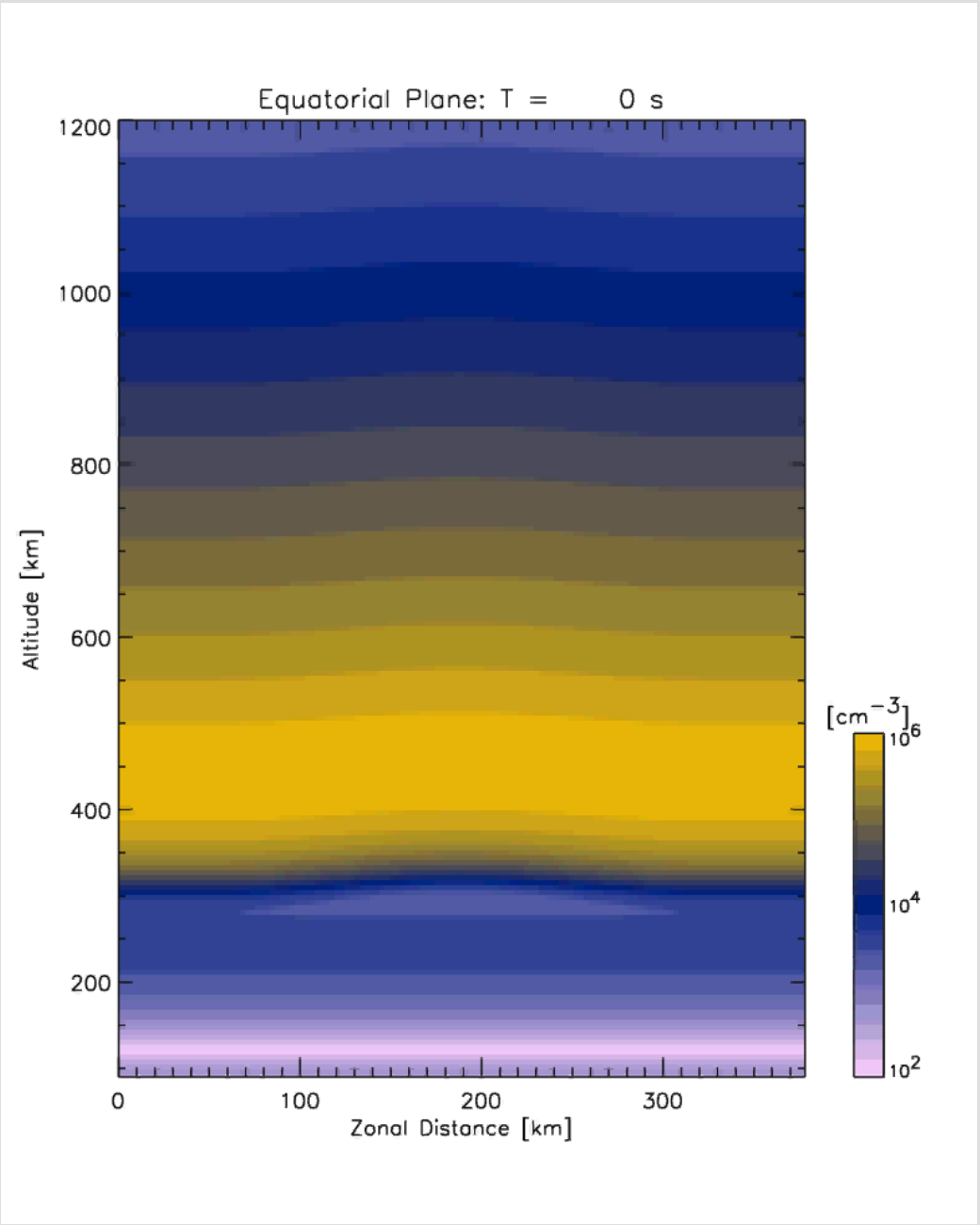






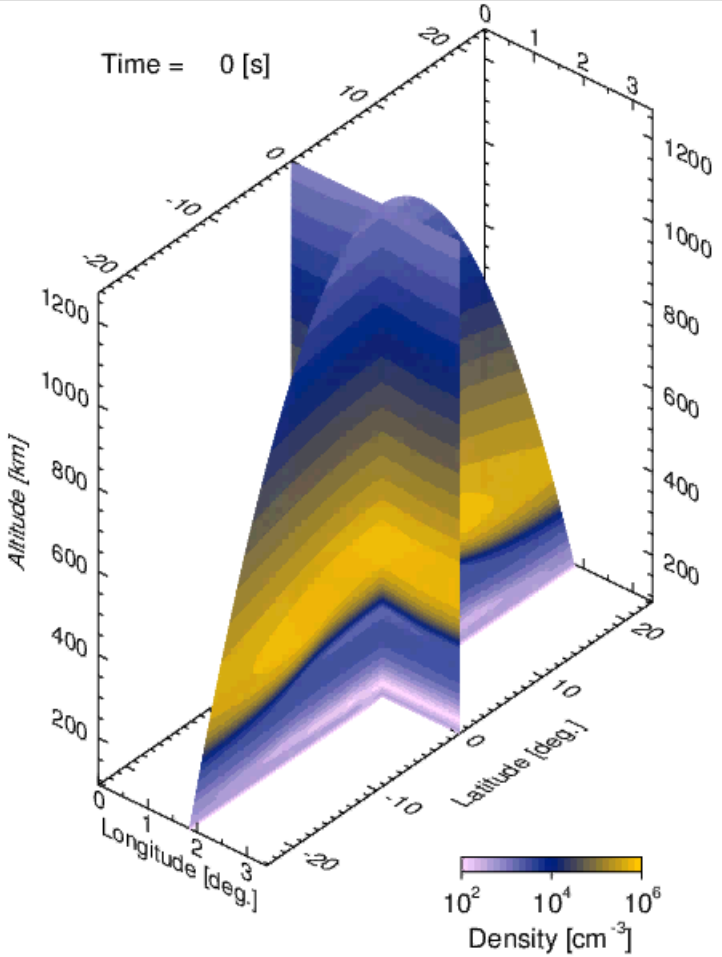
- Day: March 24, 2005, Time: 20LT, Longitude: 135°
- Apply sinusoidal perturbation by lifting the density profile to mimic LSWS.

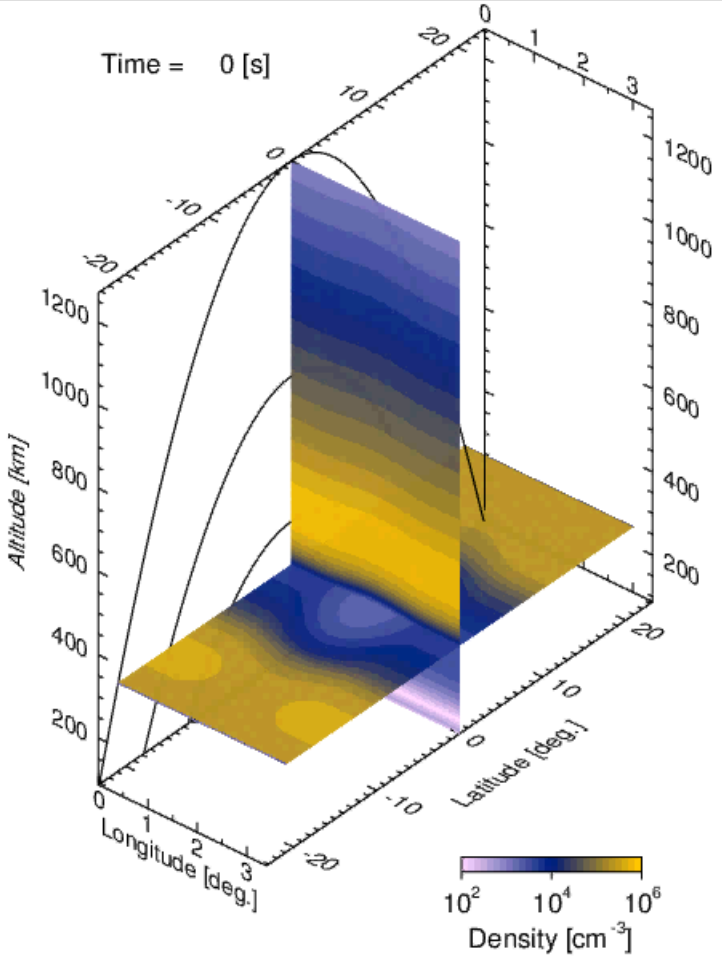
Results (no neutral wind)



Yokoyama et al. (2014)

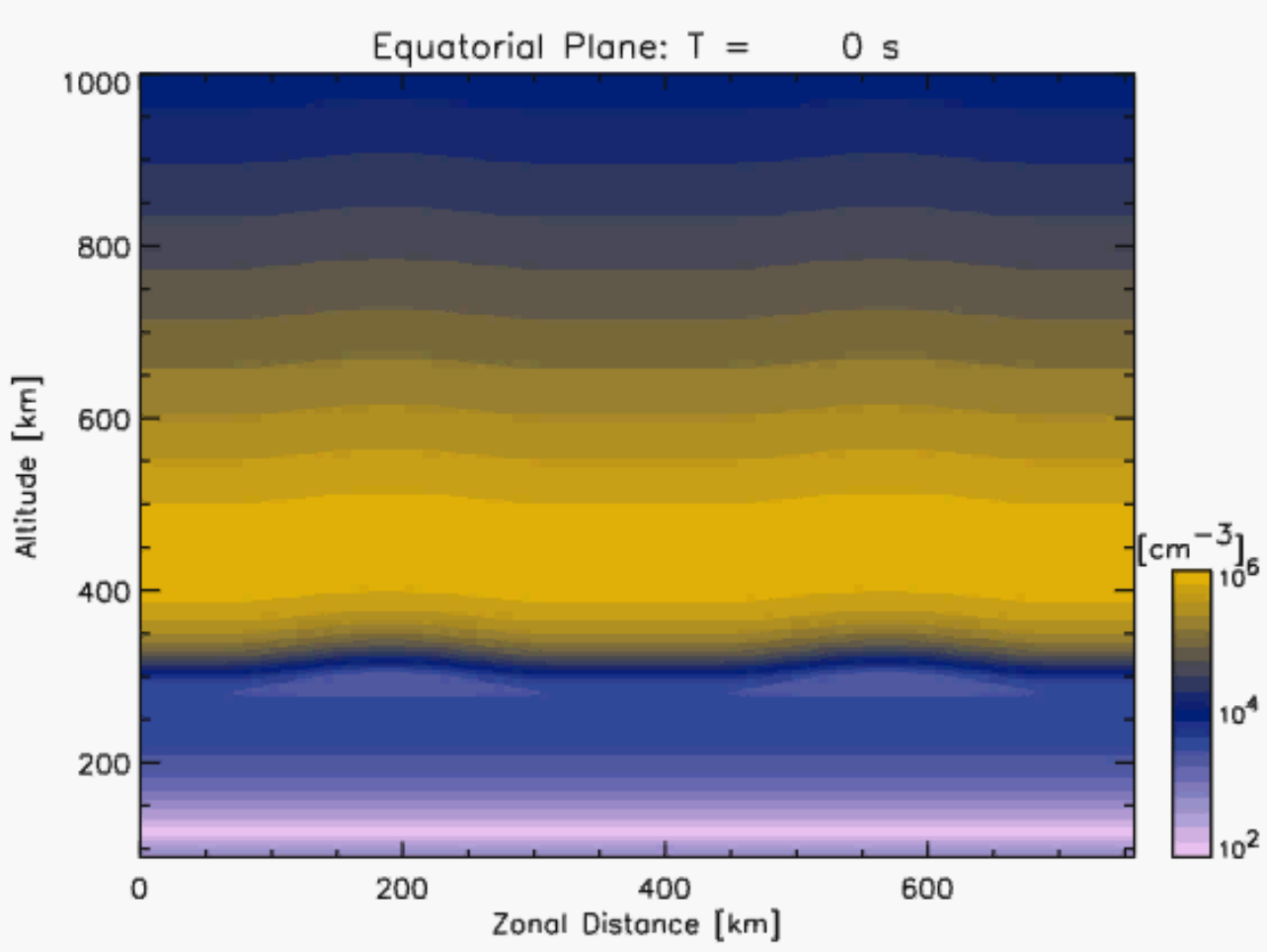
Vertical/Horizontal Density Distribution





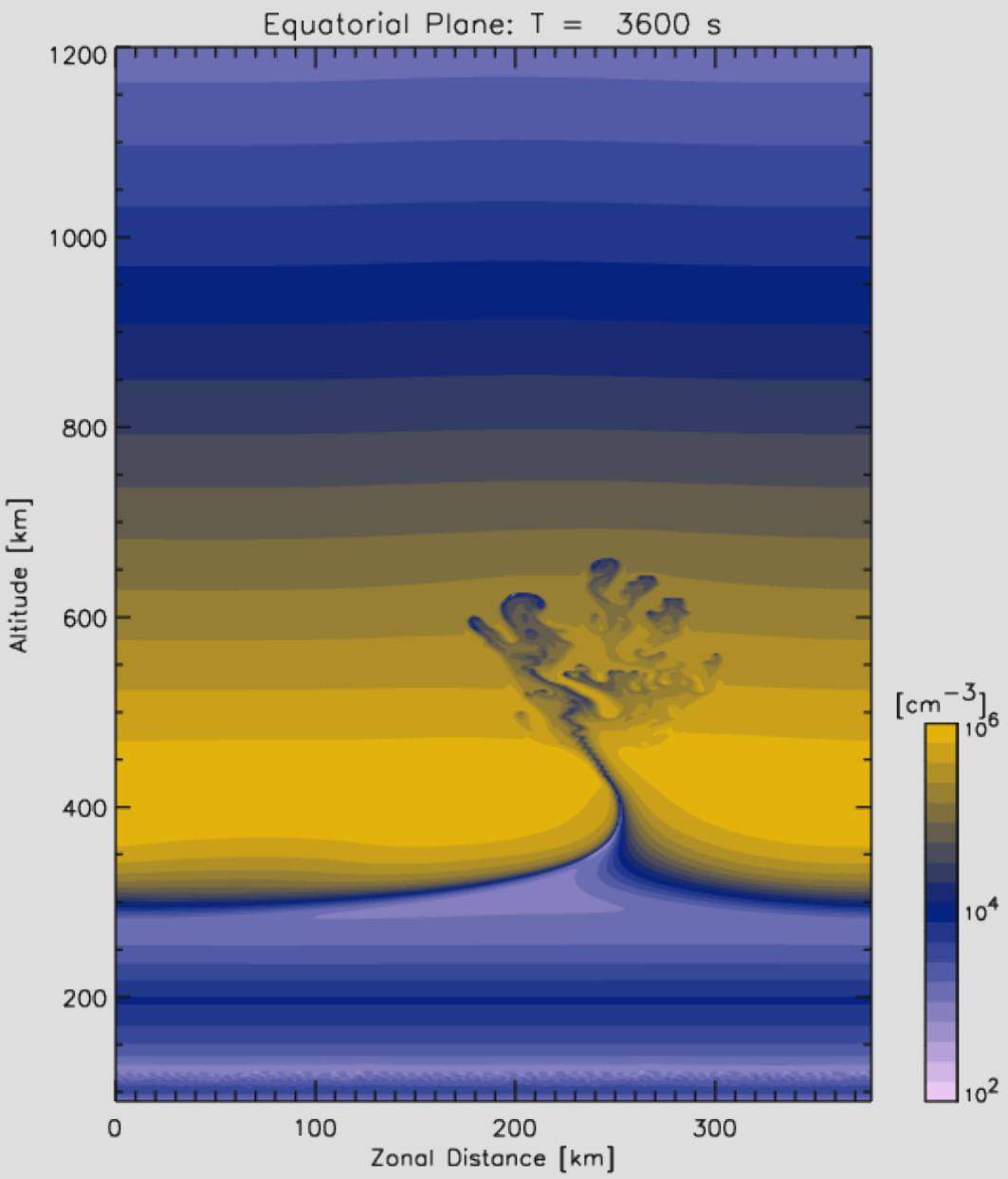
Yokoyama et al. (2014)

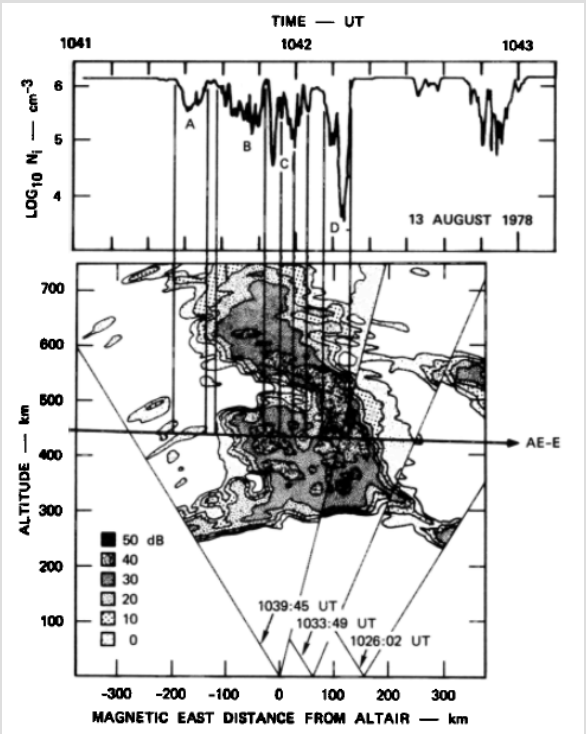
Eastward Propagation by Neutral Wind

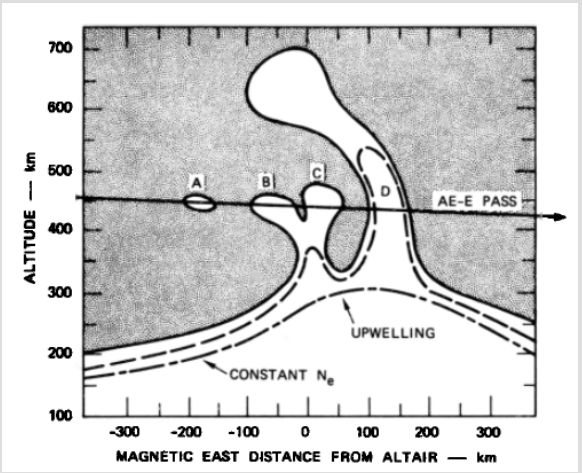


- Eastward E field turns to be westward after 1800 s.
- Eastward neutral wind produces dynamo electric field to move the bubble eastward.

LSWS at the Bottomside, Plumes at the Topside

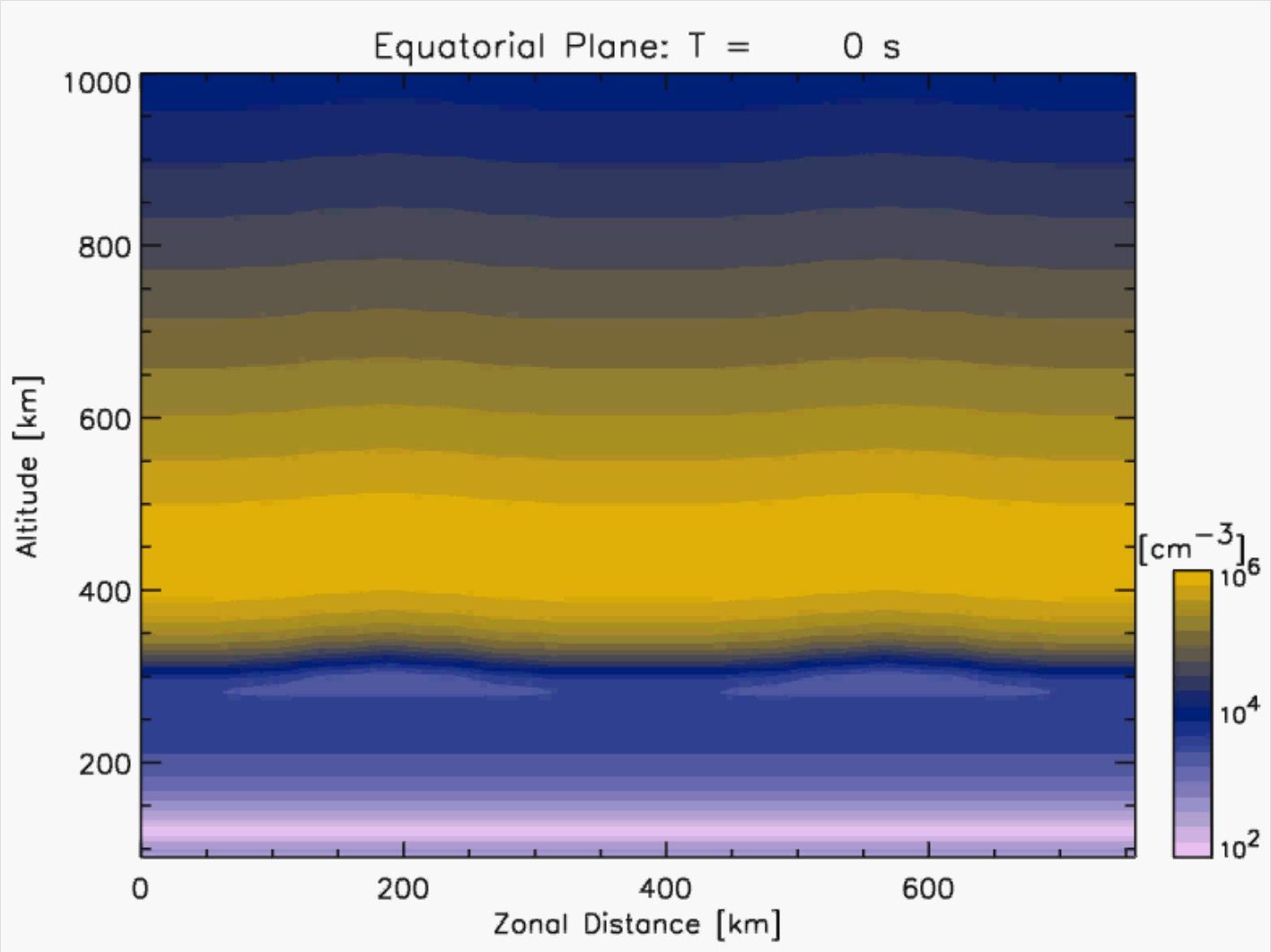


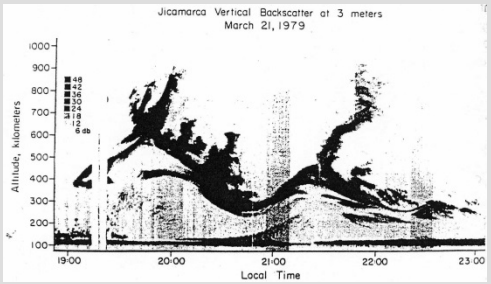




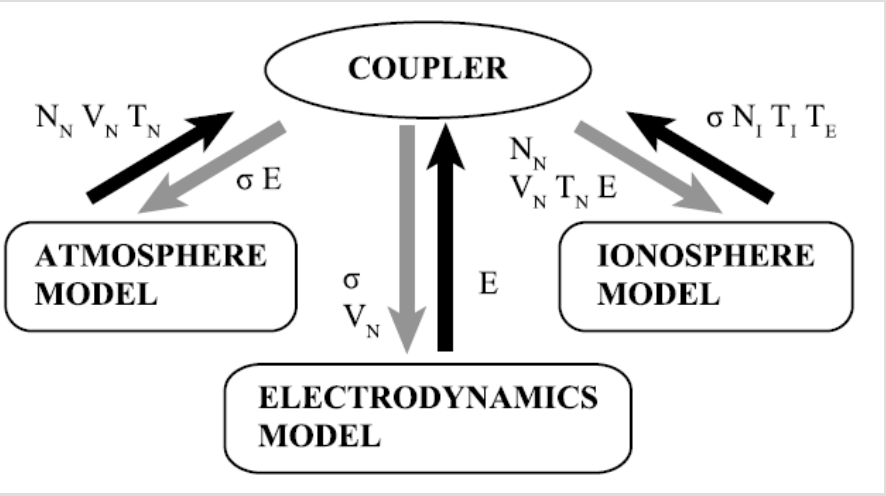
Tsunoda et al. (1982)

Western Wall Unstable

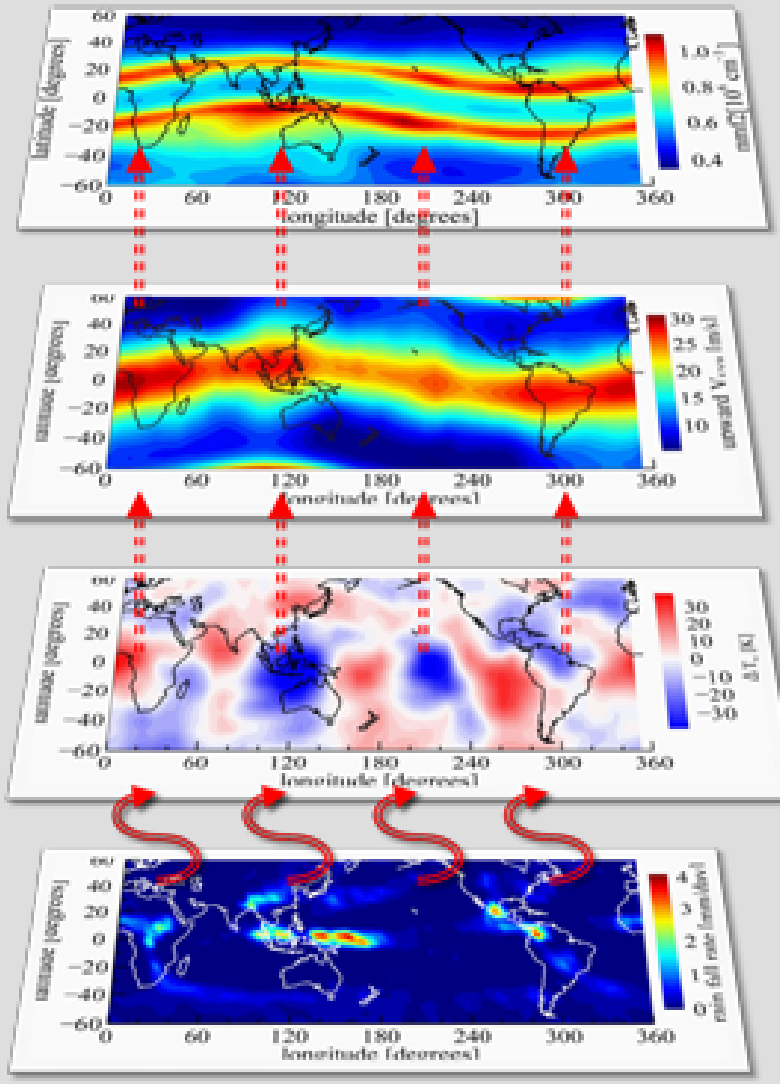




Whole Atmosphere-Ionosphere Coupled Model



- Ground-to-topside model of Atmosphere and Ionosphere for Aeronomy (GAIA) model
- Coupling with the high-resolution bubble model enables us to understand the day-to-day variability of plasma bubbles.



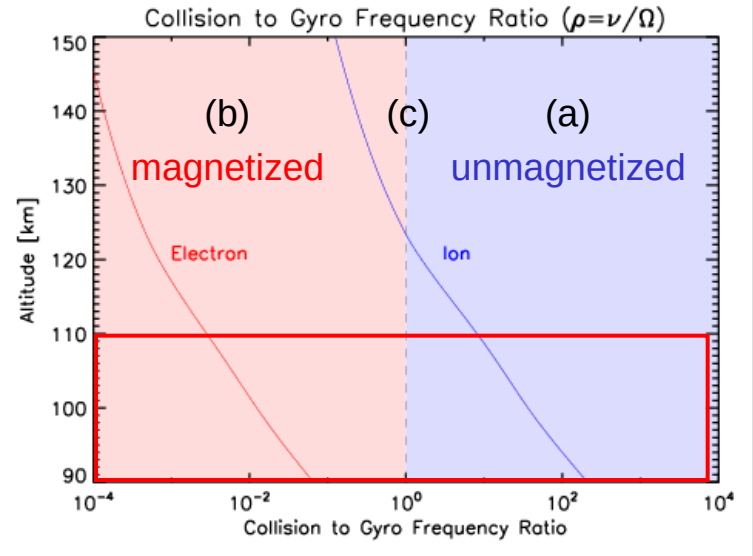
Summary

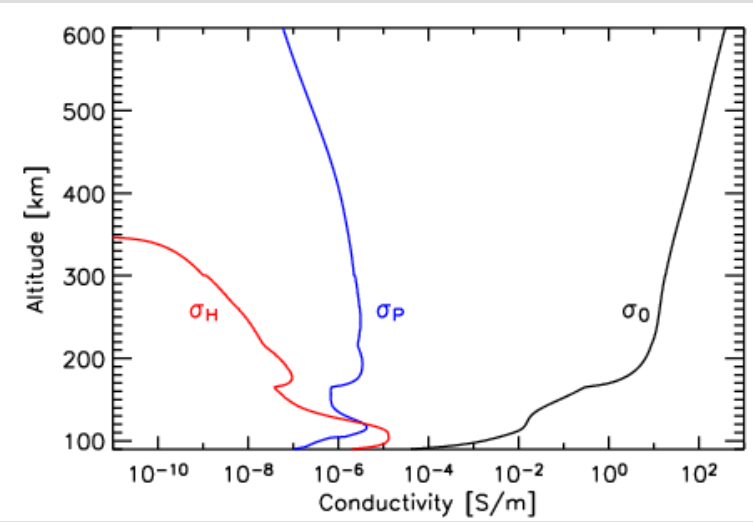
- A new three-dimensional high-resolution numerical model to study equatorial plasma bubble (EPB) has been developed with a spatial resolution of as fine as 1 km.
- Turbulent plume-like irregularities can be spontaneously generated only from large-scale perturbation at the bottomside.
- Western wall is more unstable than eastern wall.

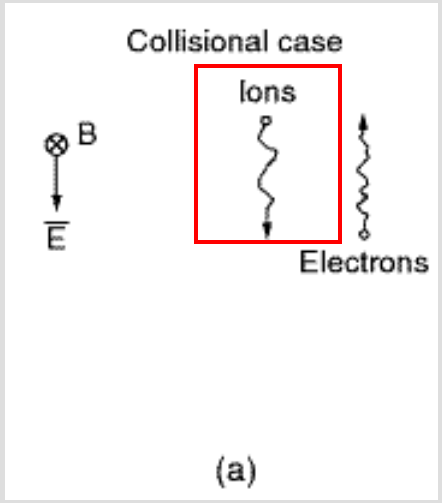
➢ Future work: Collaboration with a global model (GAIA) for background initial conditions (n, E, U, etc.)

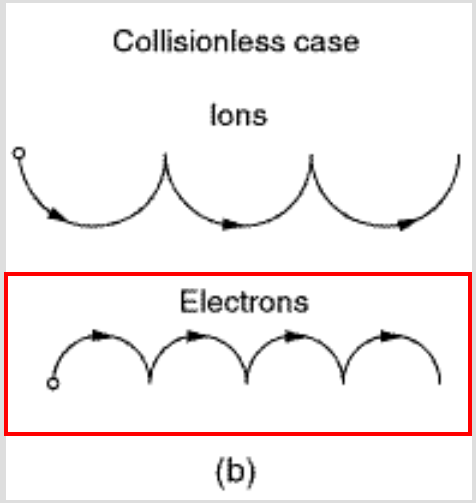
Appendix

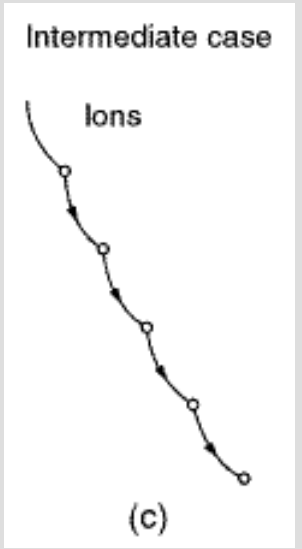
Magnetized or Unmagnetized Plasma?





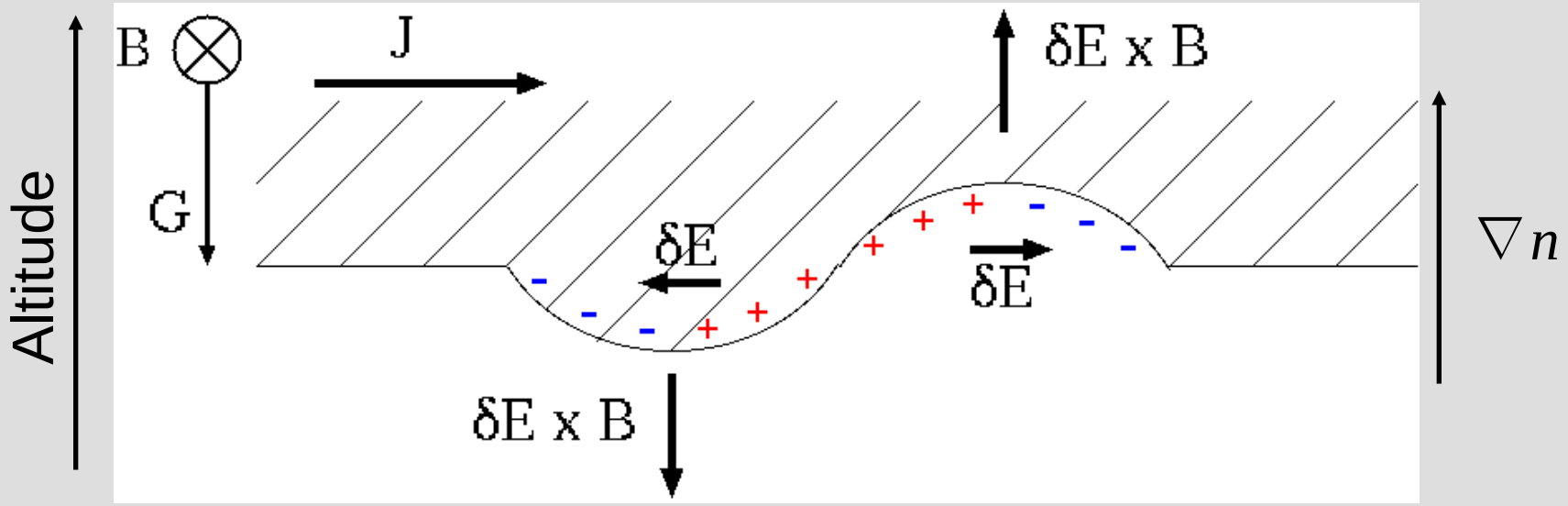






- The lower E region consists of magnetized electrons and unmagnetized ions. → Complicated electrodynamics!

Linear Growth Rate of Rayleigh-Taylor Instability



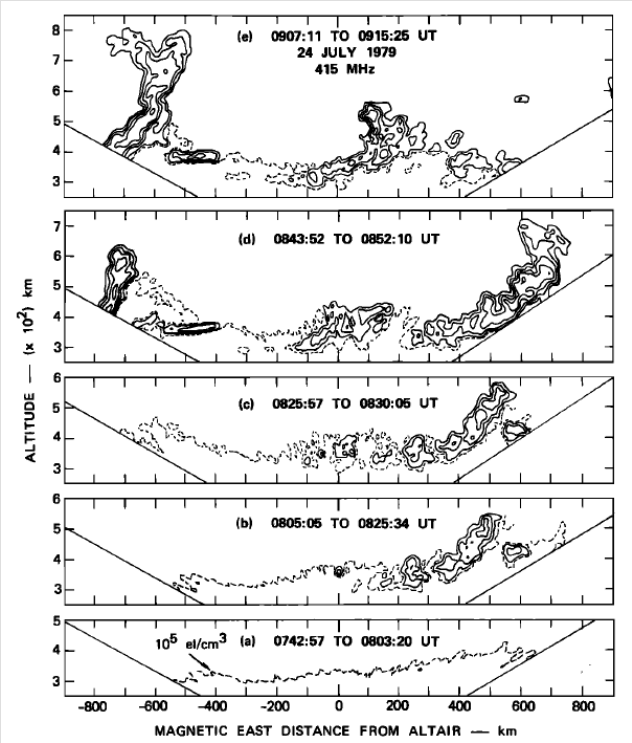
$$\gamma_L = \frac{1}{n_0}\frac{\partial n_0}{\partial z}\left(\frac{E}{B} - \frac{g}{\nu_{\text{in}}}\right) - \beta_L$$

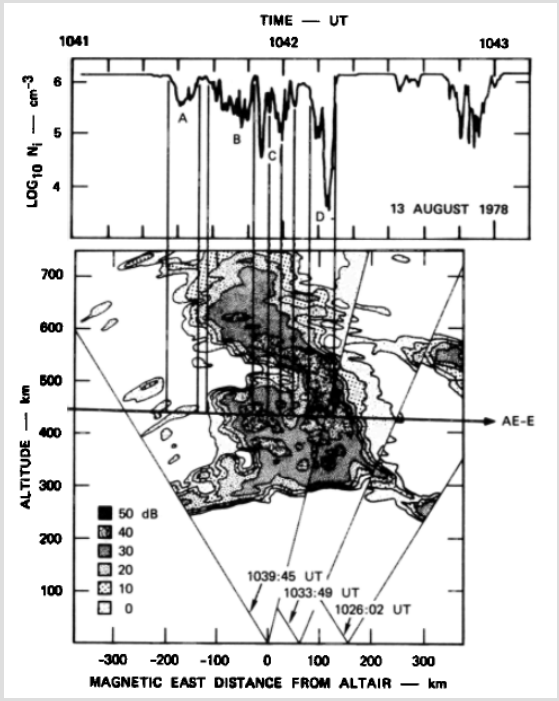
Local

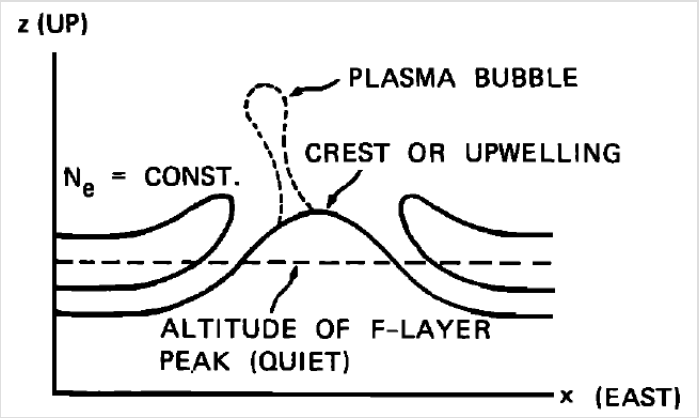
$$\gamma_{FT} = \frac{\Sigma_P^F}{\Sigma_P^E + \Sigma_P^F}\left(\frac{E}{B} - \frac{g_e}{\nu_{\text{eff}}} \cdots\right.$$

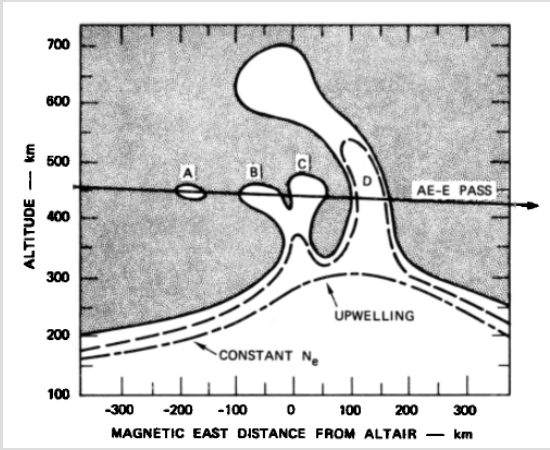
Flux-tube integrated

Large-Scale Wave Structure (LSWS)





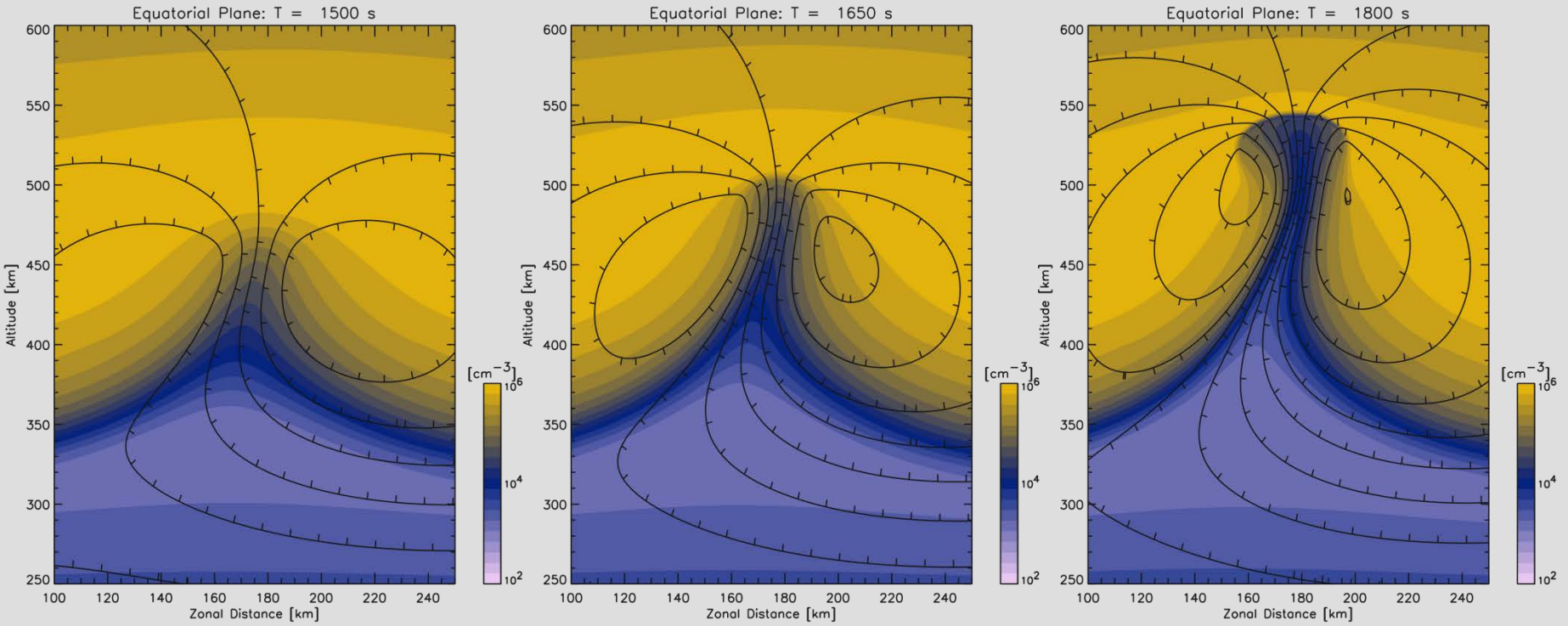




Tsunoda and White (1981)

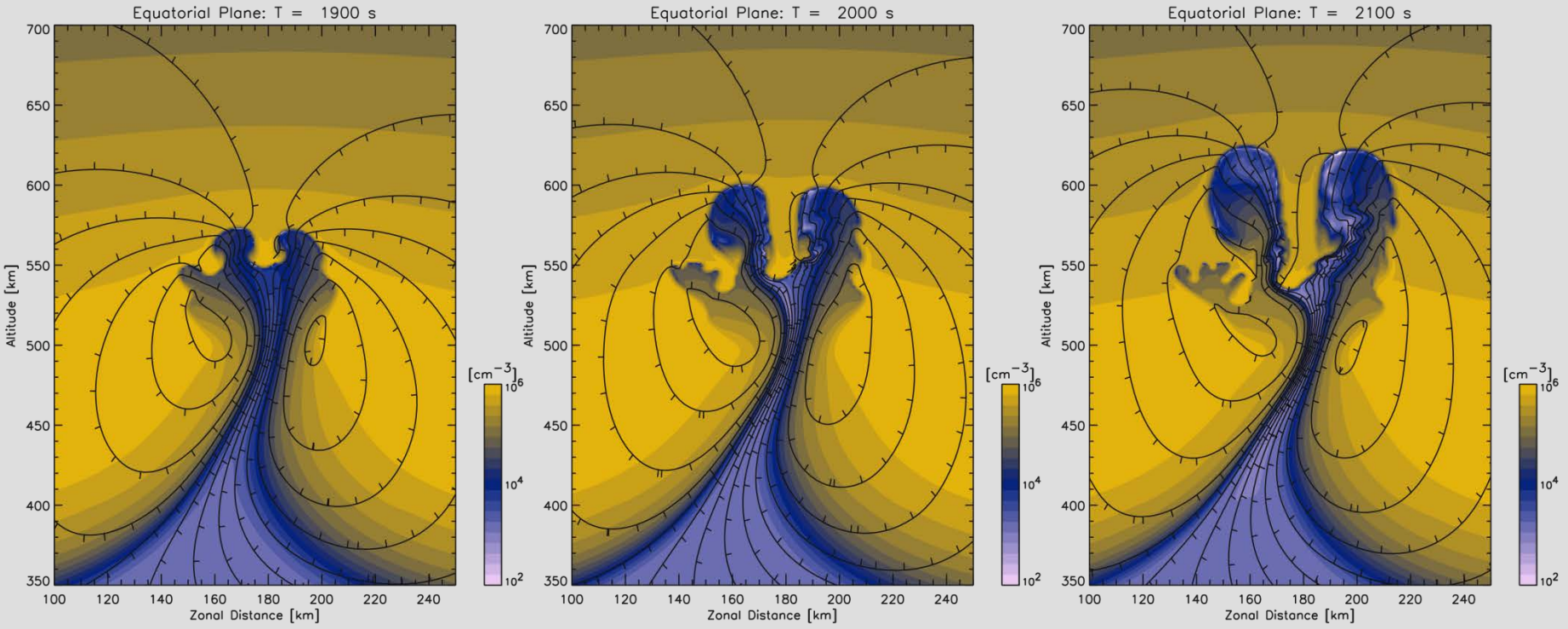
Tsunoda et al. (1982)

Forming Turbulent Structures



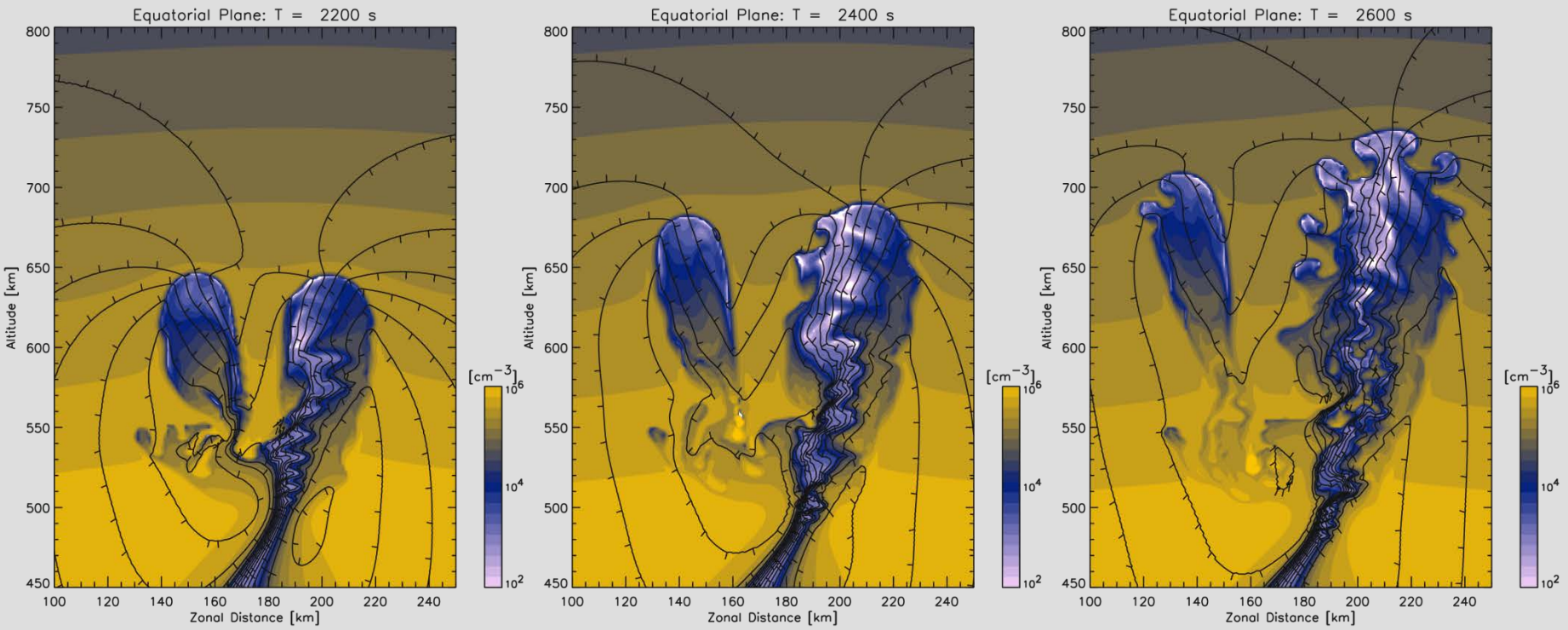
- Equipotential contours can be regarded as streamlines of plasma in the F region.
- The top of the bubble becomes flat, where the bifurcation occurs.

Forming Turbulent Structures



- After bifurcation, high density region between the two bubbles moves downward due to westward polarization electric field, then pinch off the west bubble.

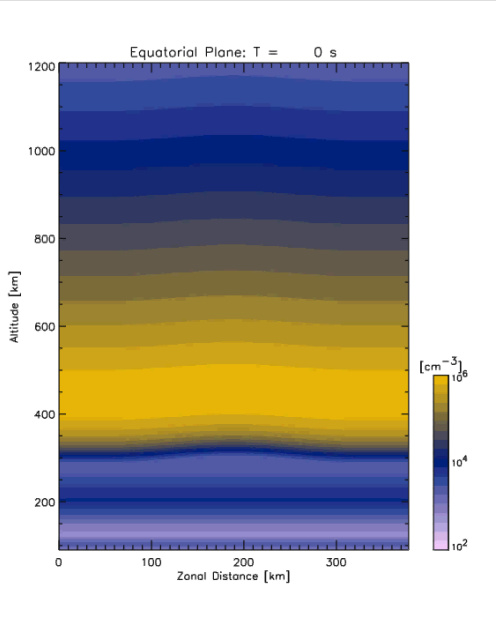
Forming Turbulent Structures



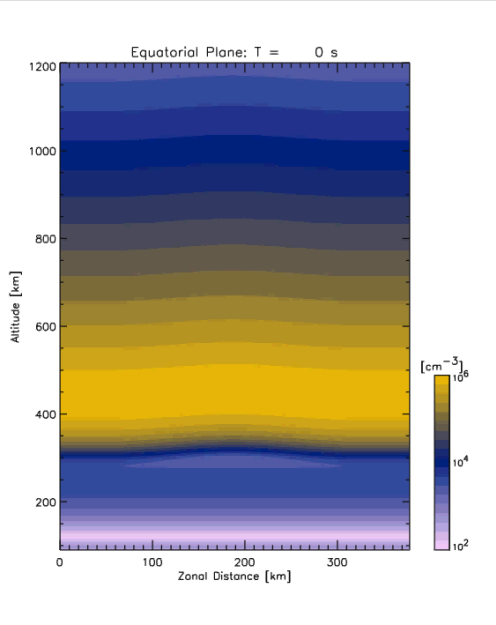
- Secondary instability occurs along the bubble wall, whereas pinched-off bubble stops growing.

Dependence on Zonal Resolution

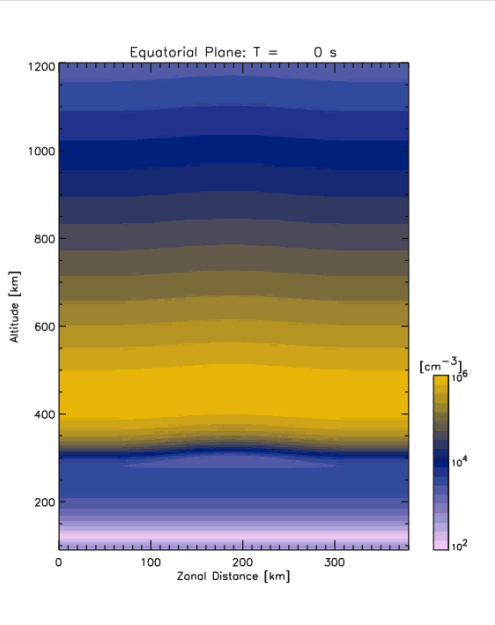
1km



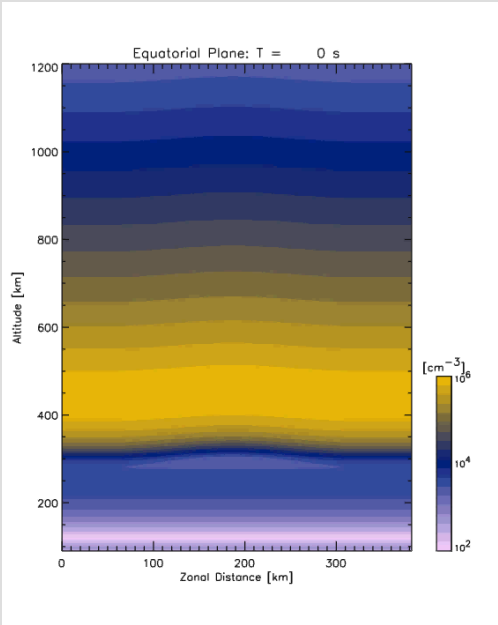
2km



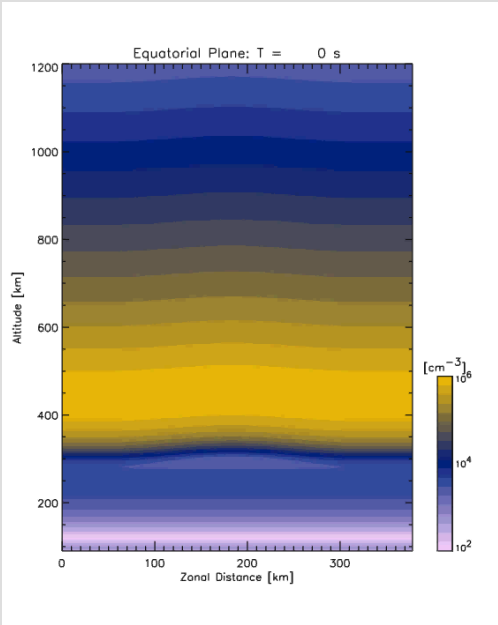
3km



4km



5km

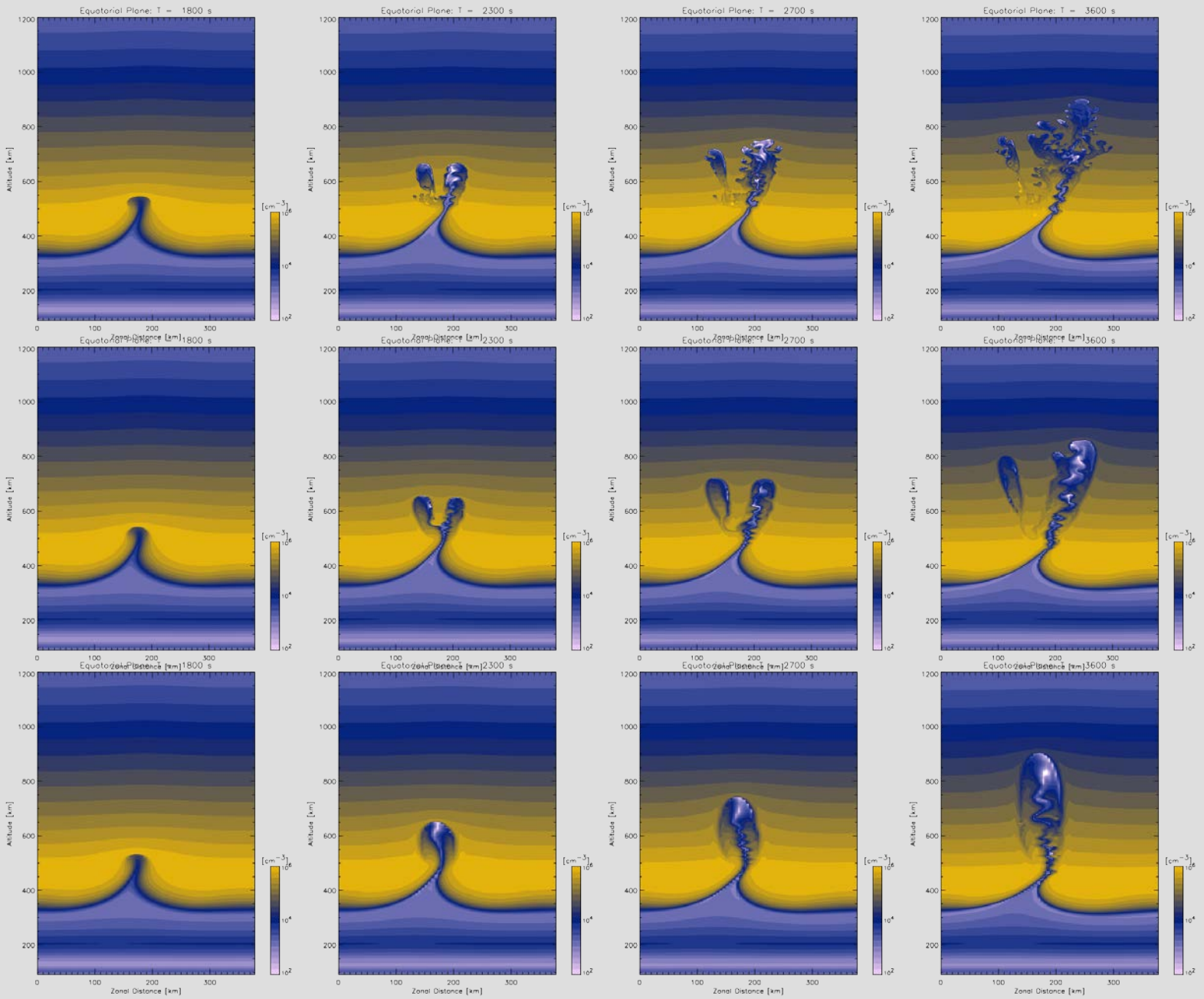


Dependence on Zonal Resolution

1km

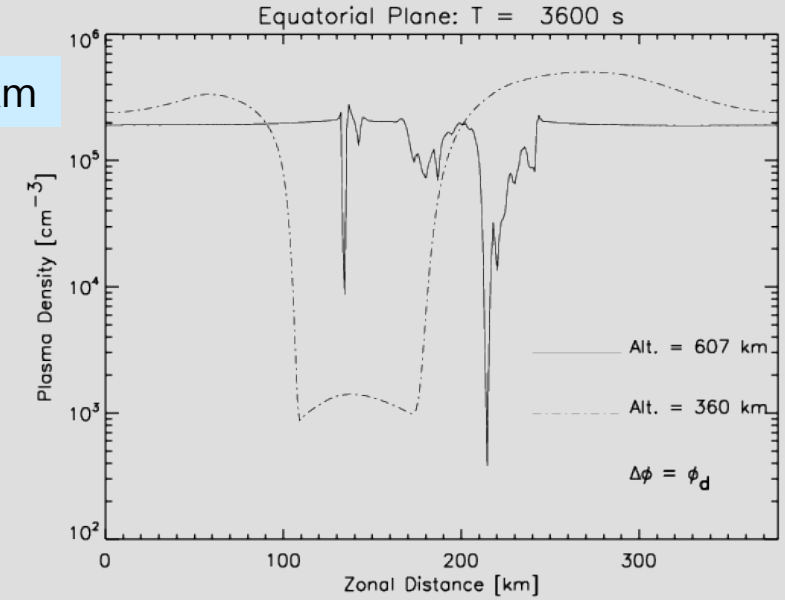
3km

5km

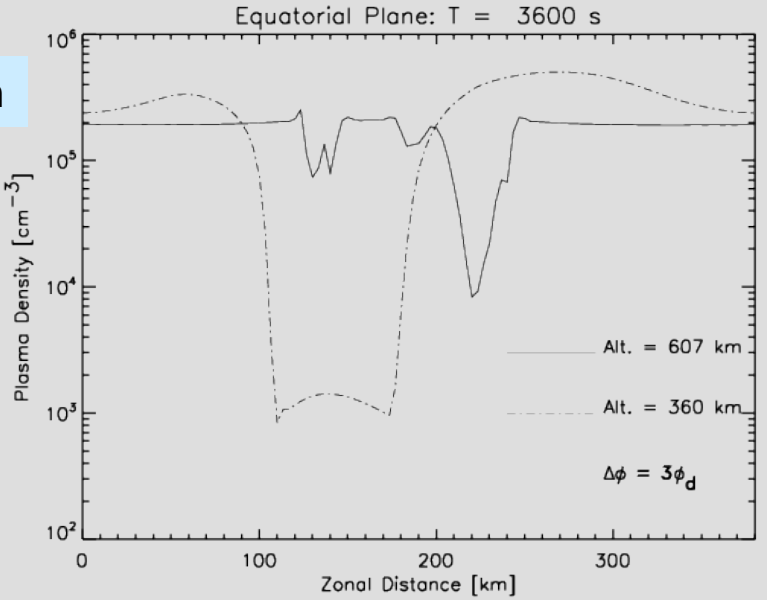


Zonal Cut

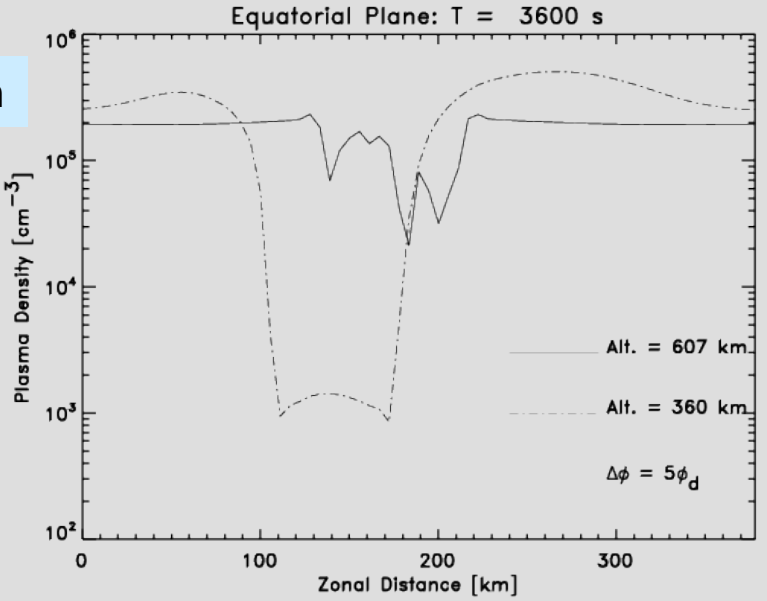
1km



3km



5km



- Topside structure depends on the grid sizes.
- Bottomside structure and vertical velocity is similar.