Workshop on Ionospheric Data Collection, Analysis and Sharing to Support GNSS Implementation

Low-Latitude Ionospheric Disturbances

With a Special Emphasis on
Equatorial Anomaly and Plasma bubbles

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Tokyo, Japan

Outline

- Ionospheric basics
  - Atmospheric models, production and loss processes
  - Geomagnetic field and Dynamics of charged particles
- Effects on radio wave propagation
  - Group delay and scintillations
- Observation techniques
  - Ionosonde / satellite beacon / in-situ measurements
- Ionospheric variations
  - 11-year solar cycle / Seasonal / daily variations
  - Equatorial anomaly
- Abrupt changes in the ionosphere
  - Negative and positive storms
  - Storm enhance density (SED)
  - Plasma bubbles
- Summary

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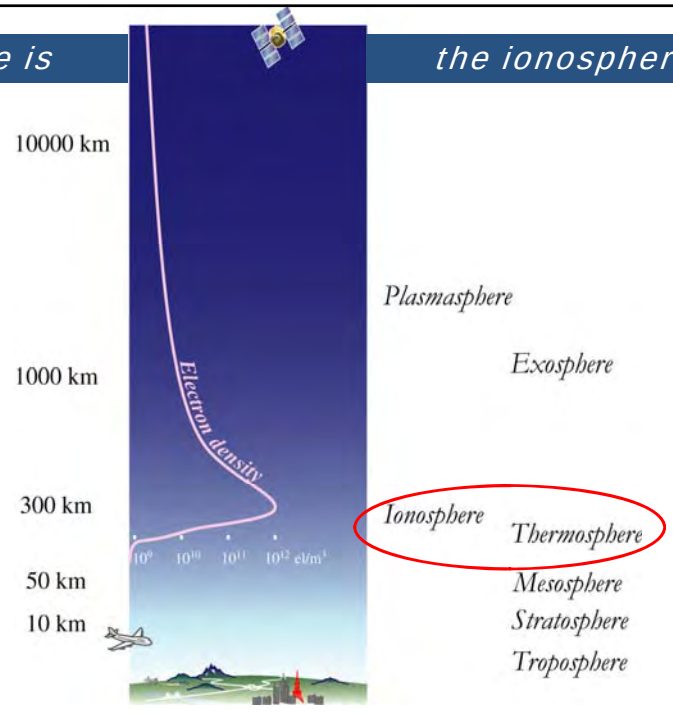
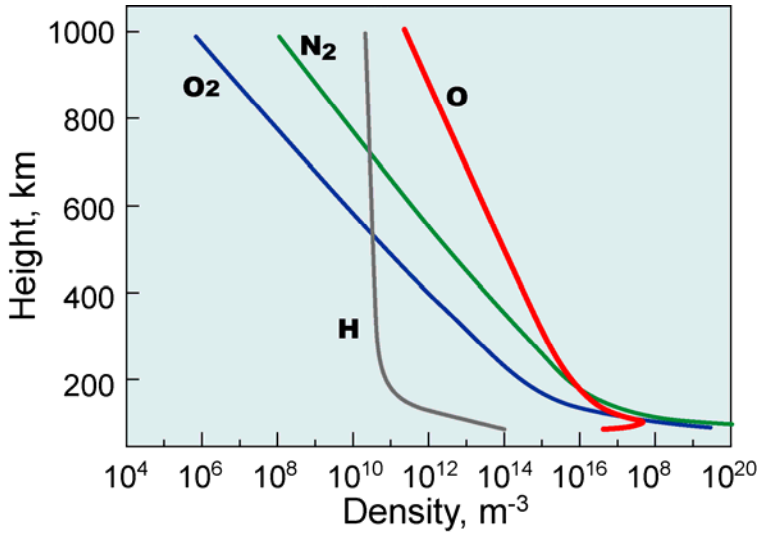
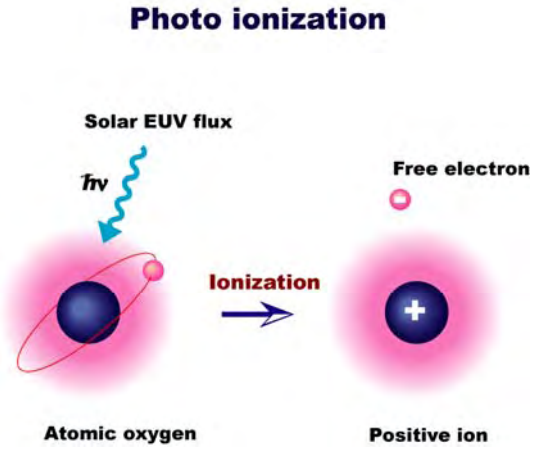
Where is the ionosphere ?



Earth's upper atmosphere – neutral particles

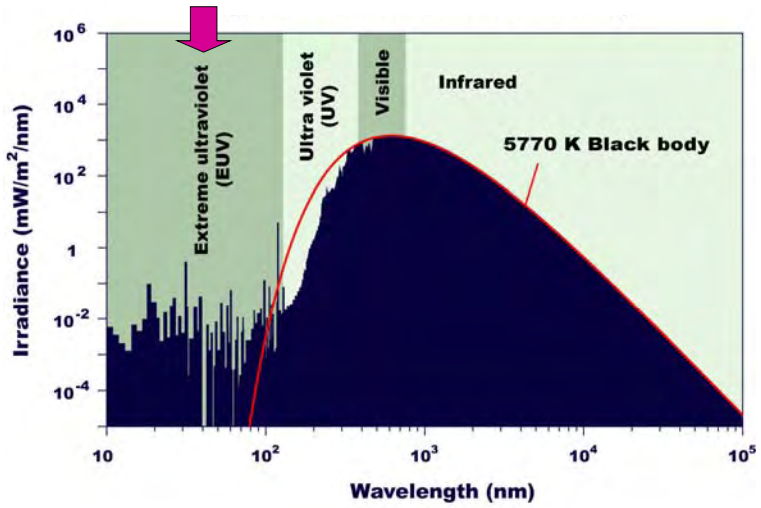


Production of ion-electron pair

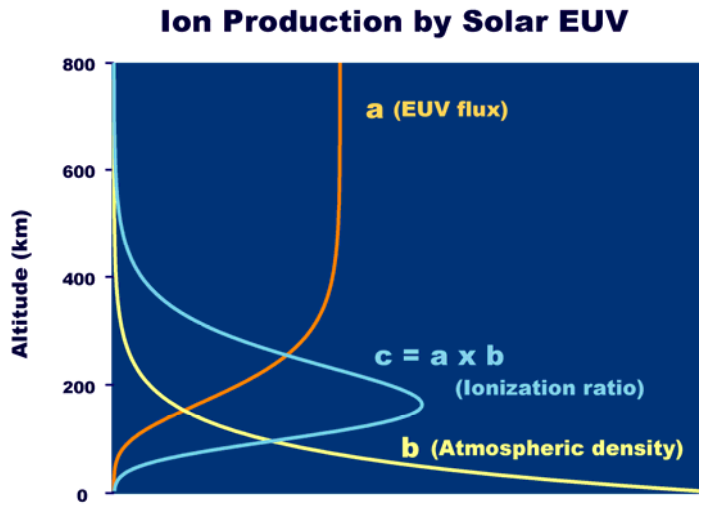


Sun's spectral Irradiance

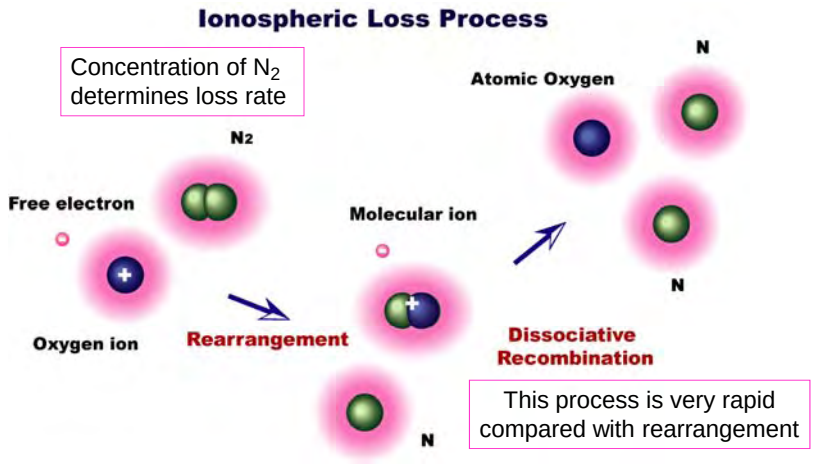
EUV radiations ionize the atmosphere: Production



Peak of ionization rate



Loss of ion – electron pair



Height variation of recombination rate

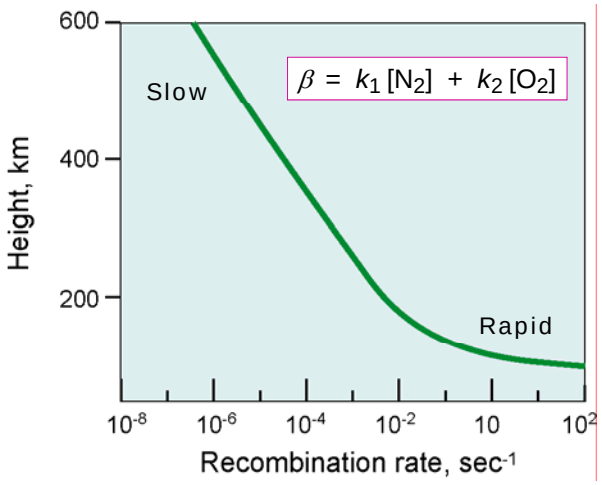


Photo-chemical equilibrium

P ~ Solar EUV flux

L ~ βN_e

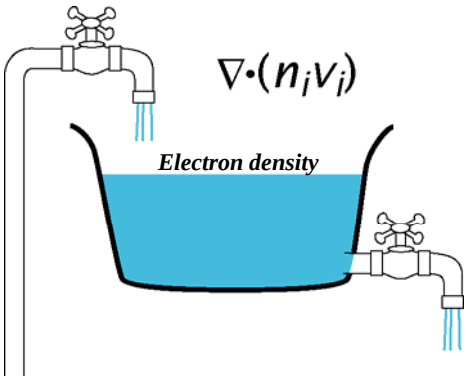
β = loss coefficient
N_e = electron density

$P = L \Rightarrow N_e = P/\beta$

$\beta = k_1 [N_2] + k_2 [O_2]$

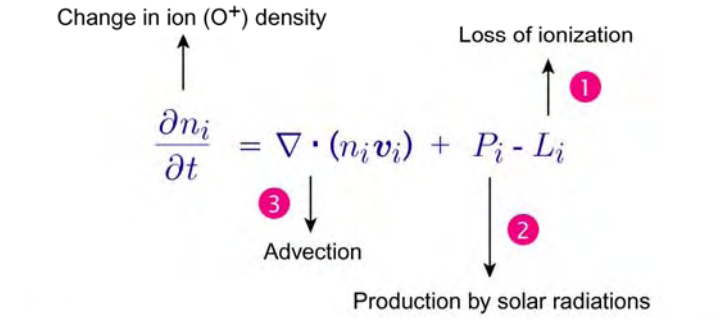
How is the electron density determined

Chemical equilibrium is not sufficient to explain N_e variations



How is the electron density determined

Ion continuity Equation in the F-region



The balance of 1 to 3 determines steady state ionosphere

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Free electron affects radio propagation

$$\text{Refractive index } (\mu) = \sqrt{1 - 2A \frac{\text{Electron denisty (n)}}{(\text{Frequency (f)})^2}}$$

$$\text{Group refractive index } (\mu') = \frac{\text{Light velocity (c)}}{\text{Group velocity } (v_g)} = \frac{d}{df}(f\mu)$$

$$= \frac{1}{\sqrt{1 - 2A \frac{\text{Electron density (n)}}{(\text{Frequency (f)})^2}}}$$

Free electron affects radio propagation

$$\text{Group refractive index } (\mu') = \frac{\text{Light velocity (c)}}{\text{Group velocity } (v_g)}$$

For micro wave used in satellite communications and GPS

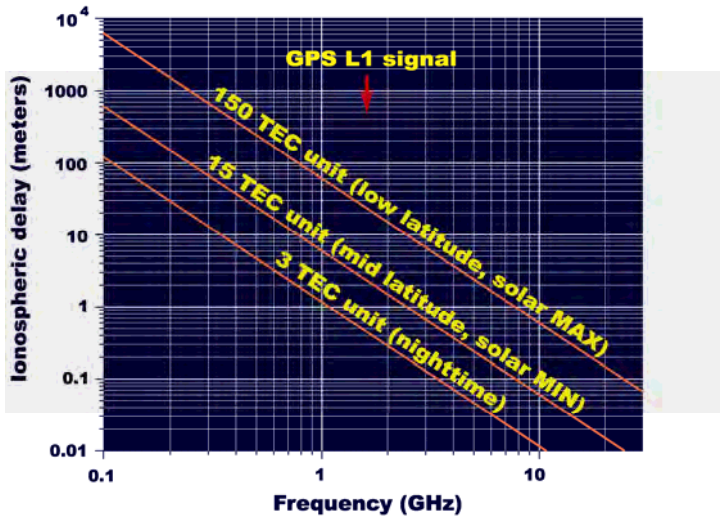
$$\mu' = 1 + A \frac{\text{Electron density (n)}}{(\text{Frequency (f)})^2}$$

$$\text{Delay time } (\Delta t) = \int_s \left(\frac{1}{v_g} - \frac{1}{c} \right) ds$$

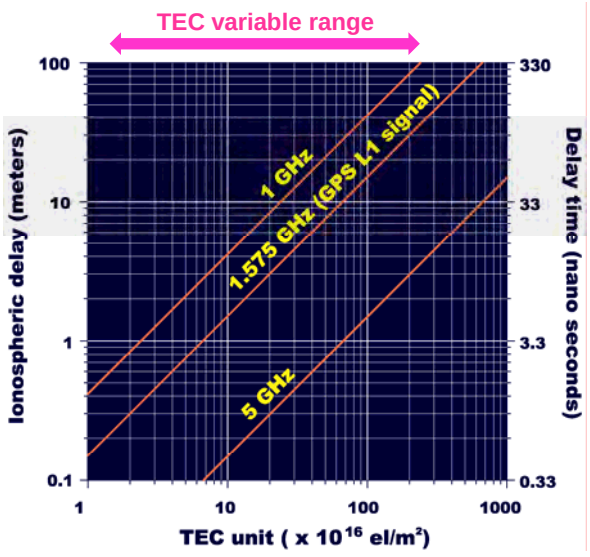
$$= \frac{A}{cf^2} \int_s n\,ds$$

Total electron content

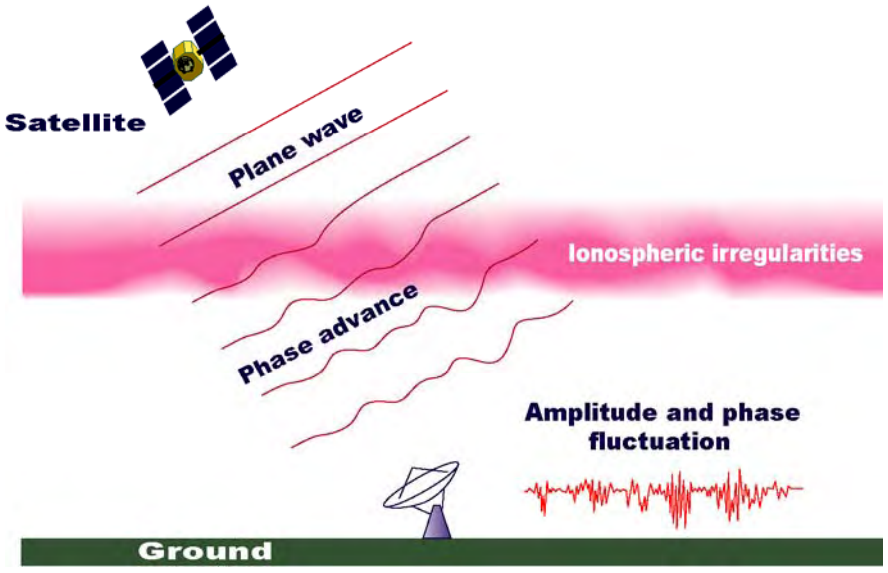
Ionospheric delay



Ionospheric delay



Ionospheric scintillation



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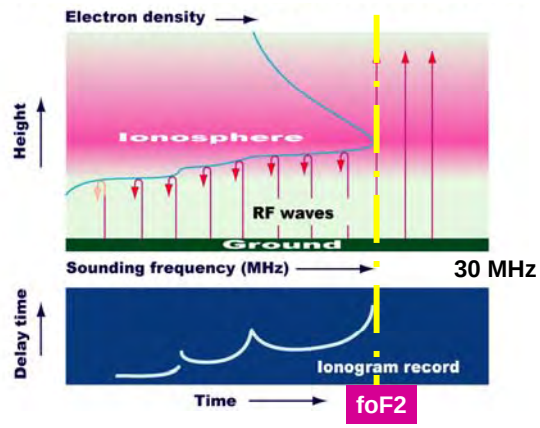
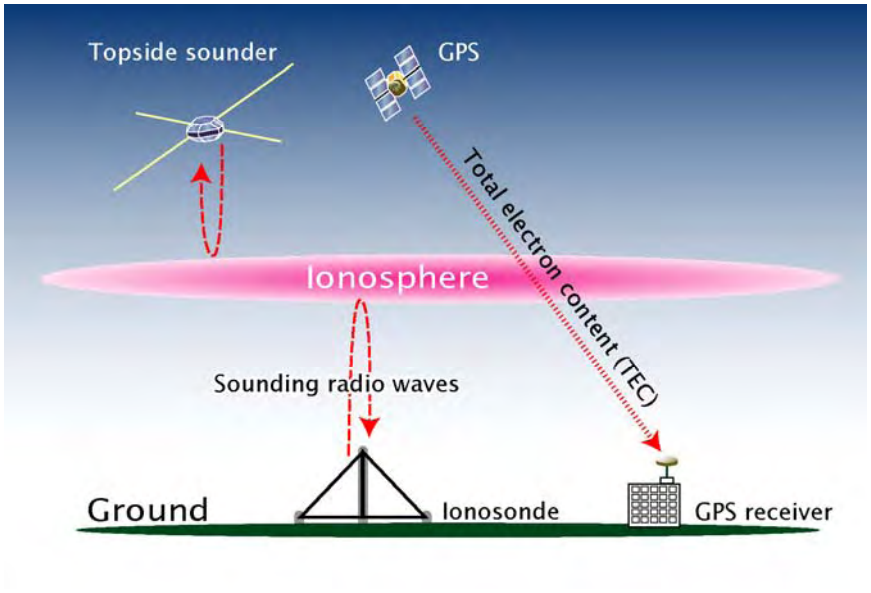
Ionospheric observation

Ionosonde



Ionospheric critical frequency (foF2) is a most important parameter and corresponds to a maximum electron density (NmF2).

Ionospheric observation



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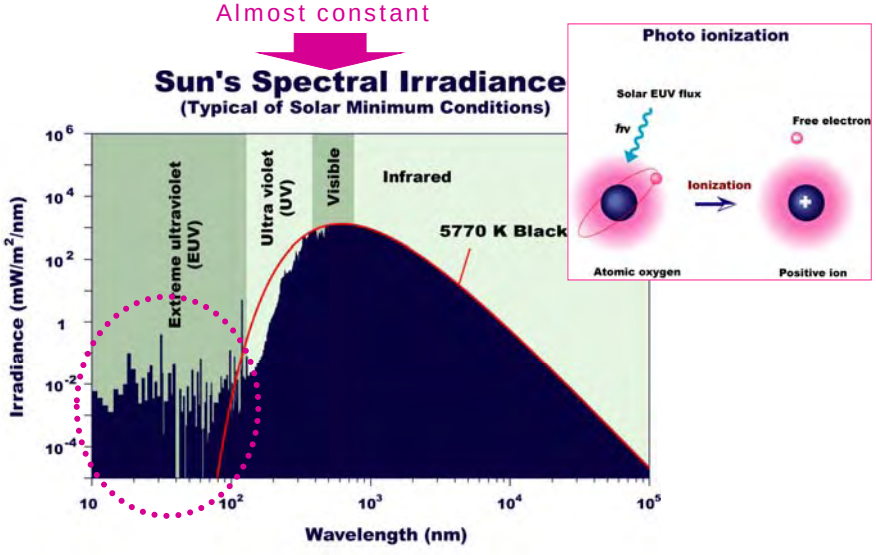
Sun's spectral Irradiance

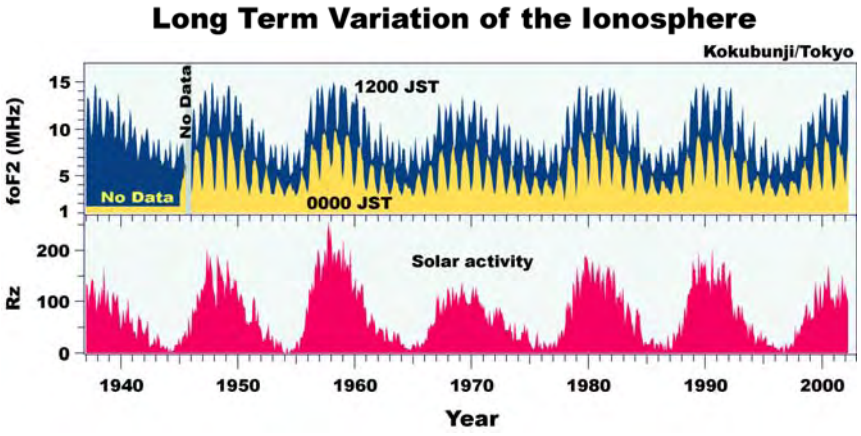
Almost constant



EUV is quite variable

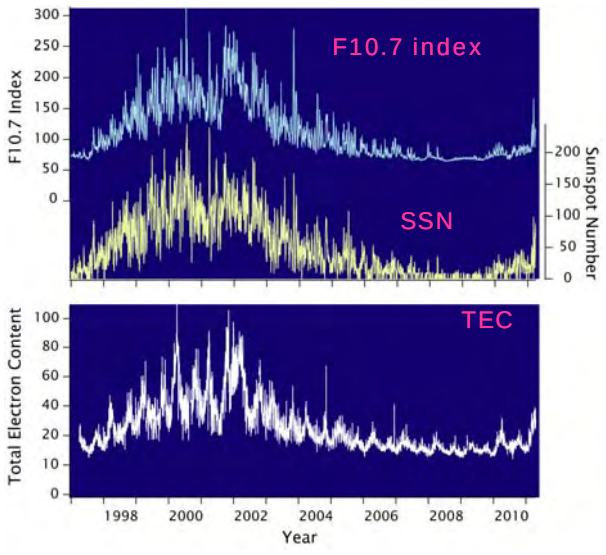
Solar dependence (6 solar cycles)

Sunspot number (Rz) is a good proxy of solar EUV irradiance



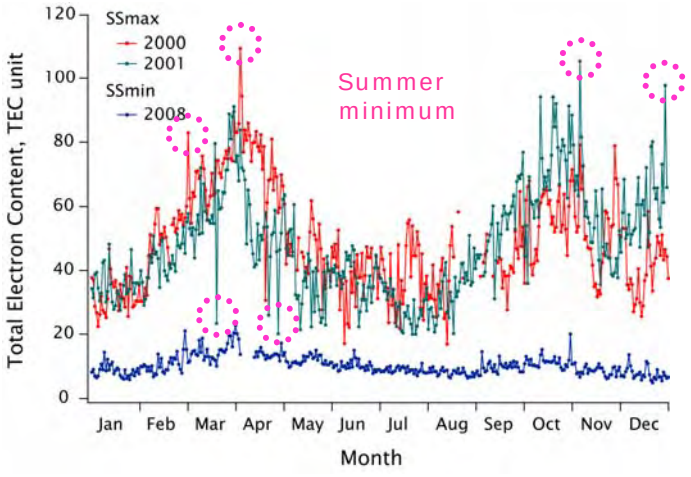
Variations for April 1997 – March 2011

New cycle started



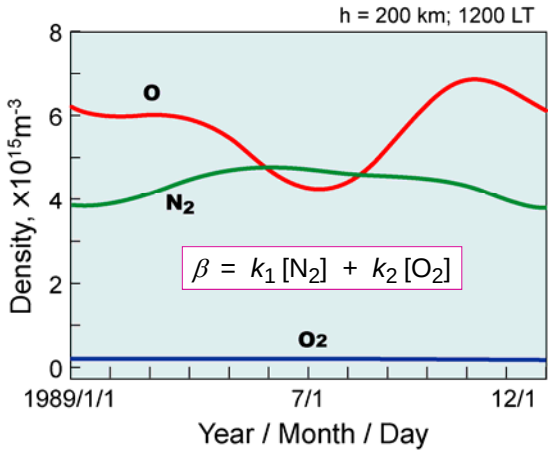
Seasonal variations for SS max and min

Large deviations are ionospheric storms



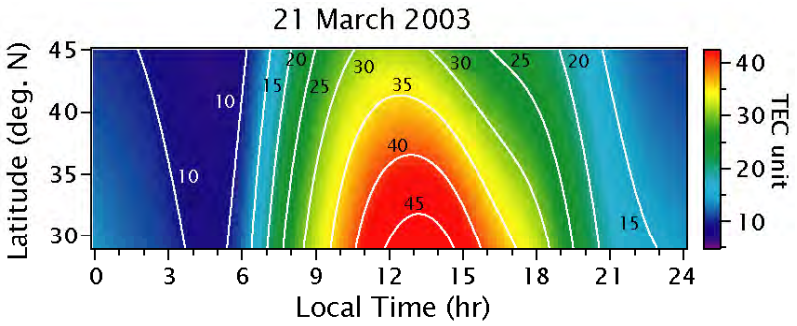
Seasonal anomaly or summer minimum

Small [O]/[N_2] ratio causes the summer minimum of ionospheric density



MSIS empirical atmospheric model

Local time and latitude variations



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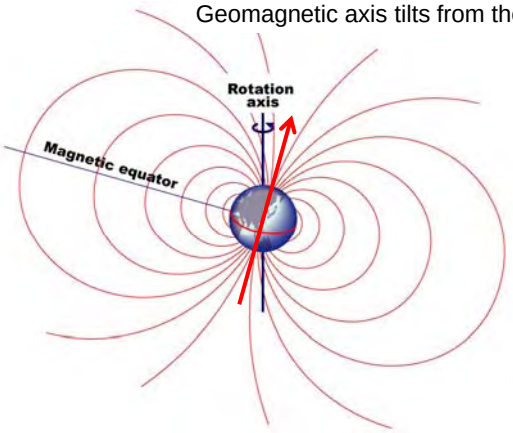
The earth is a big magnet

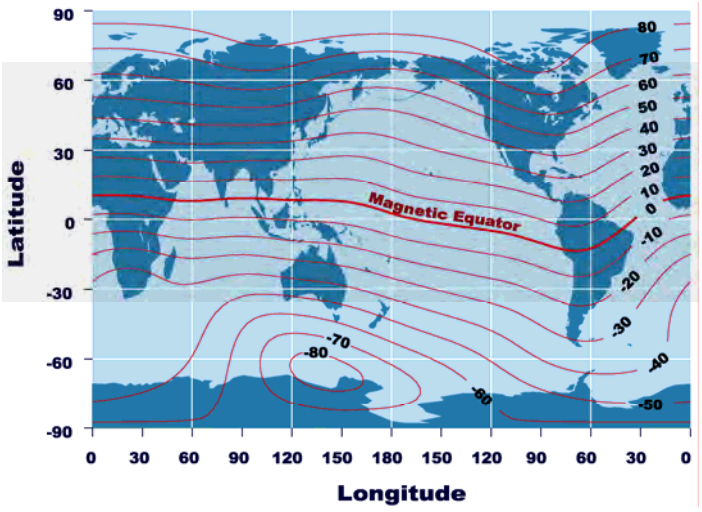
Charged particles (ion and electron) are trapped in the magnetic field in the ionospheric F region

Geomagnetic axis tilts from the rotation axis



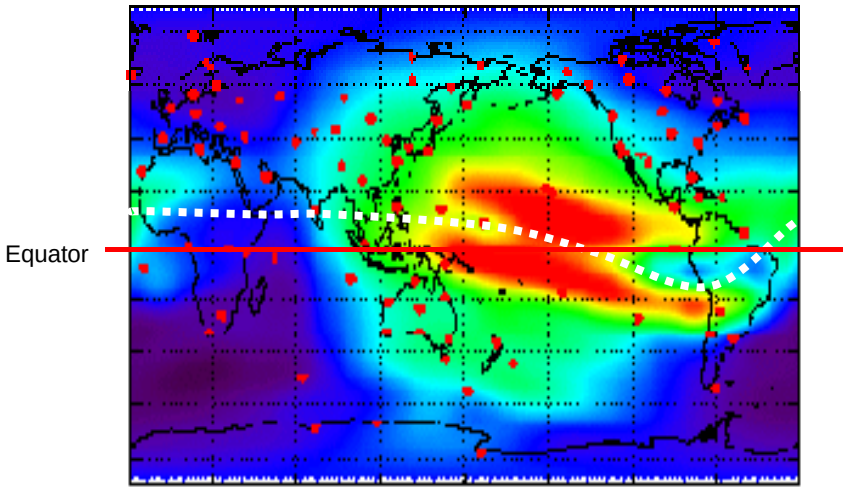
Magnetic coordinate

Ionospheric structure is strongly affected by the magnetic field



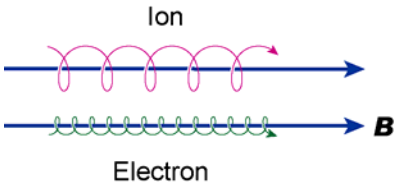
Global ionospheric map; JPL

Snap shot of total electron content distribution by GPS network

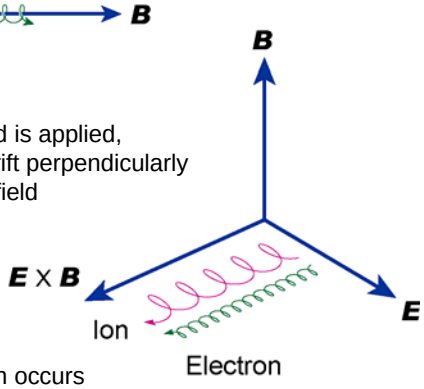


Motion of charged particles in M-field

Ions and electrons are easily move along the magnetic field line but movement perpendicular to the M-field line is restricted.



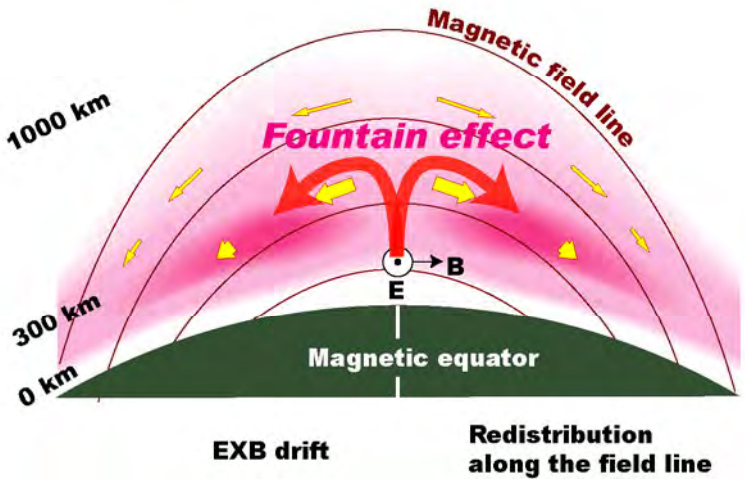
When external E-field is applied, ions and electrons drift perpendicularly to the E-filed and M-field



No charge separation occurs

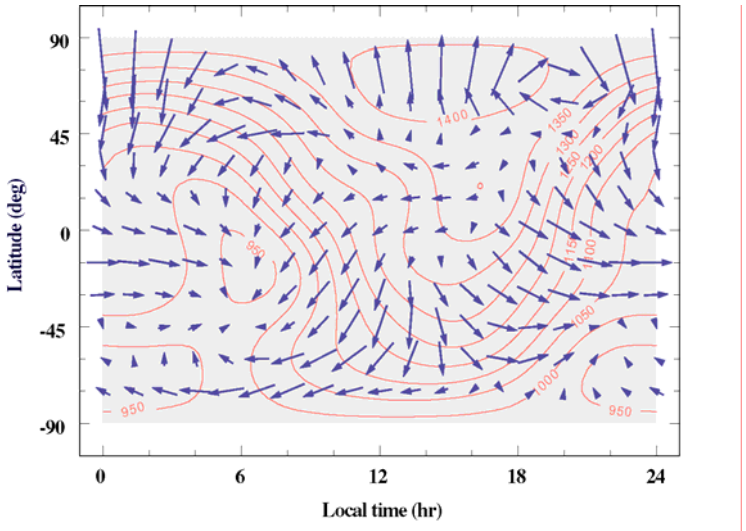
Formation mechanism of equatorial anomaly

Fountain effect

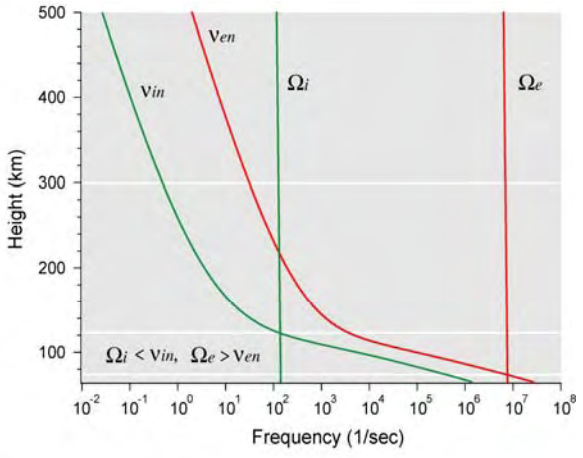


Origin of E-field

Neutral wind blows from dayside to nightside



Collision and gyro frequencies



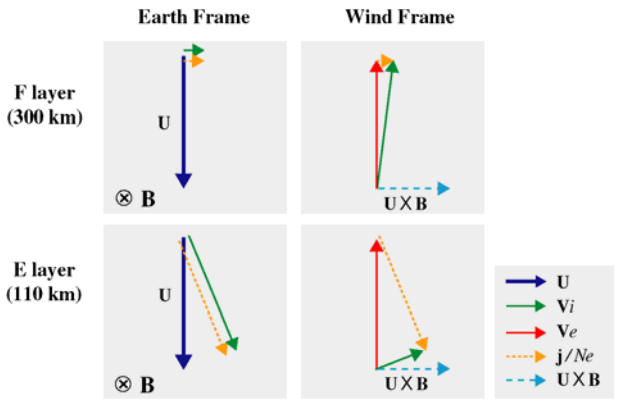
F-region

E-region

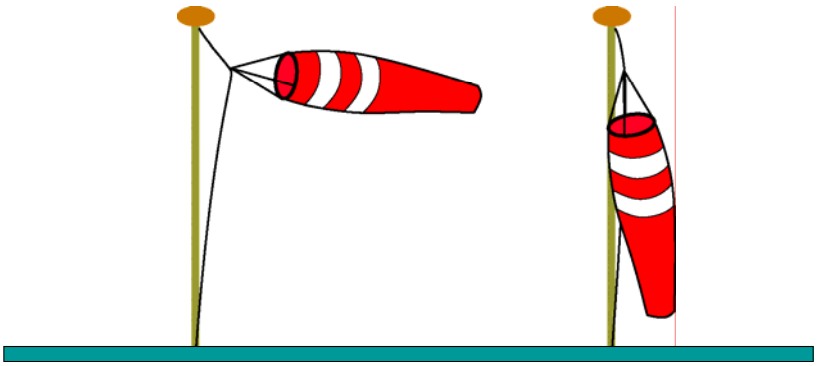
MSISE90 / IGRF: Day = 081; Lon = 140E; Lat = 35N; LST = 1200; ion = NO+

Ion motion by neutral wind (dynamo)

Different motion of ions and electrons causes charge separation. The electric field generated in the E region is mapped into the F region along the magnetic field line, which is the driver of equatorial anomaly.



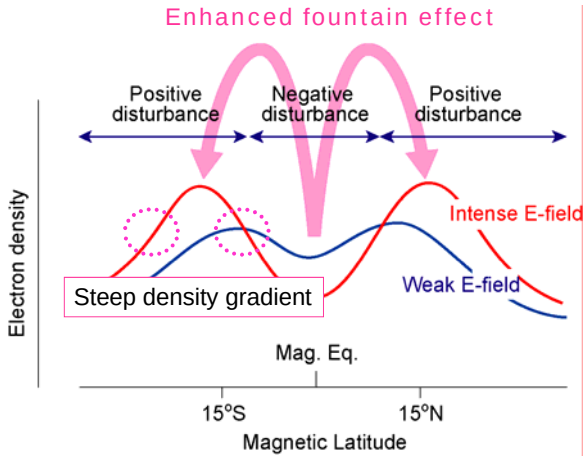
Neutral wind varies day by day



Neutral wind is not constant everyday and ionospheric dynamo E-field varies, and equatorial anomaly too.

Complicated response to E-field near the M.E.

Generally, eastward electric field causes a positive storm.
However, response is complicated near the magnetic equator



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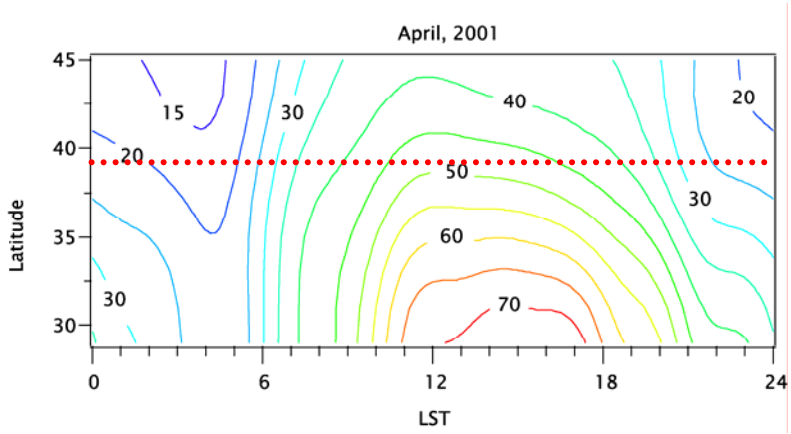
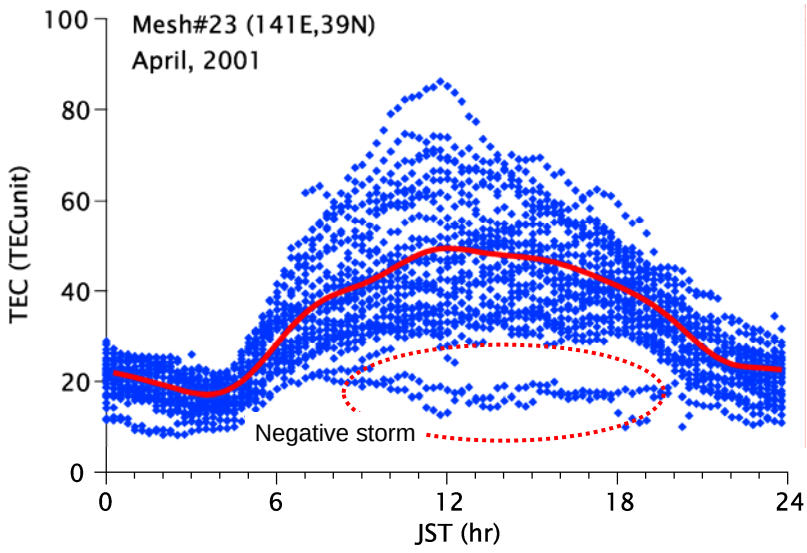
Local time – latitude variations (TEC)

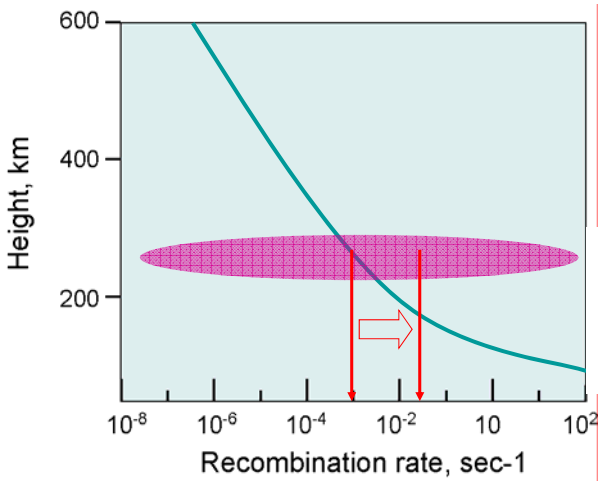


TEC averaged over one month

Mass plots of TEC daily variation for one month

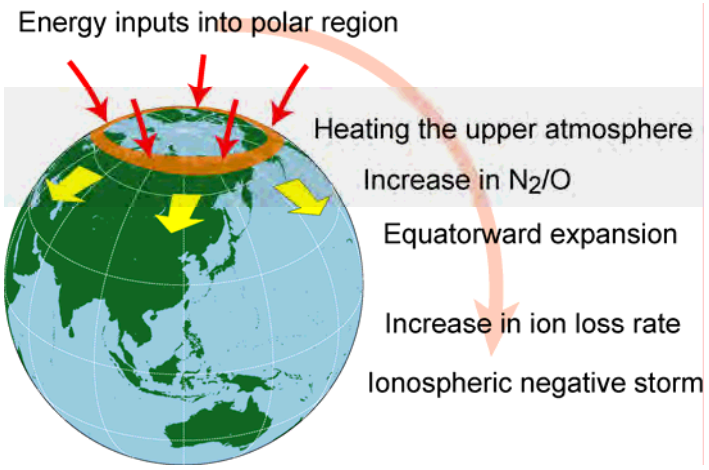


Mechanism of negative storm



N_2 increases ➡ Recombination rate increases ➡ Density decreases

During magnetic disturbances



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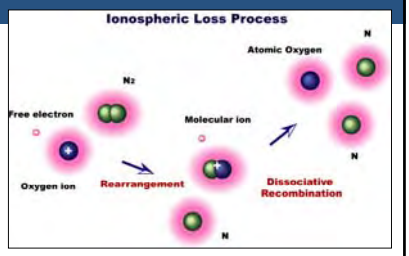
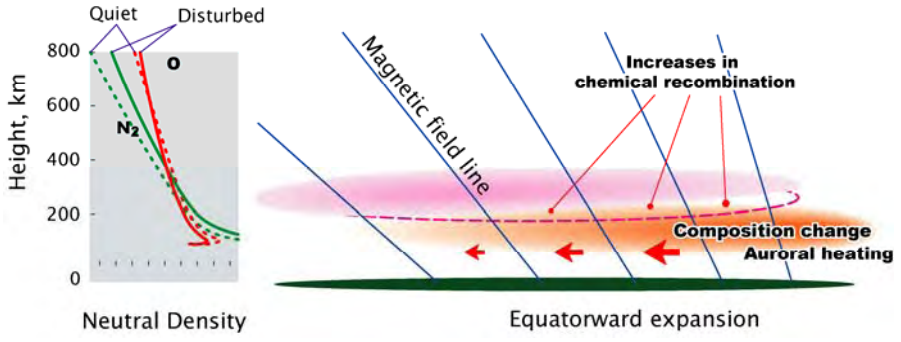
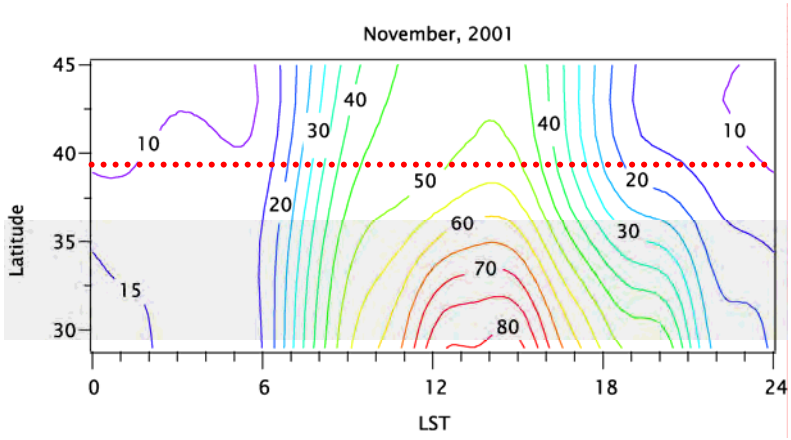




~ 150 m/sec

Local time – latitude variations (TEC)



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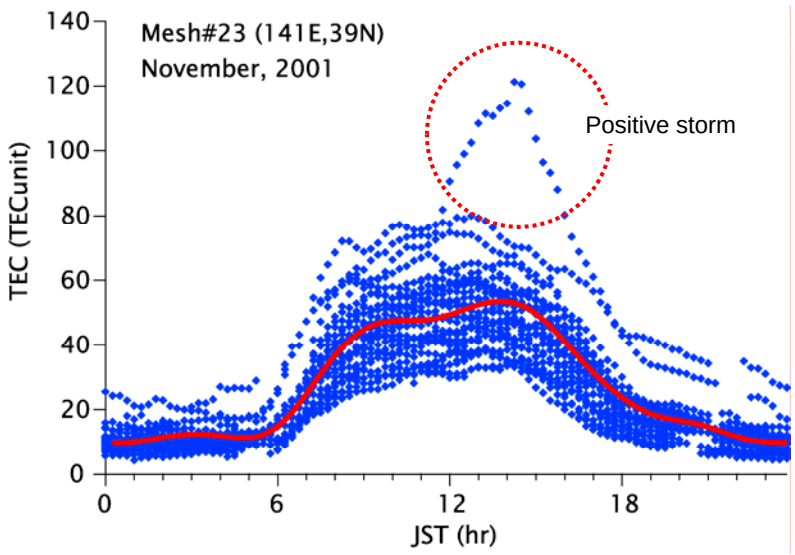
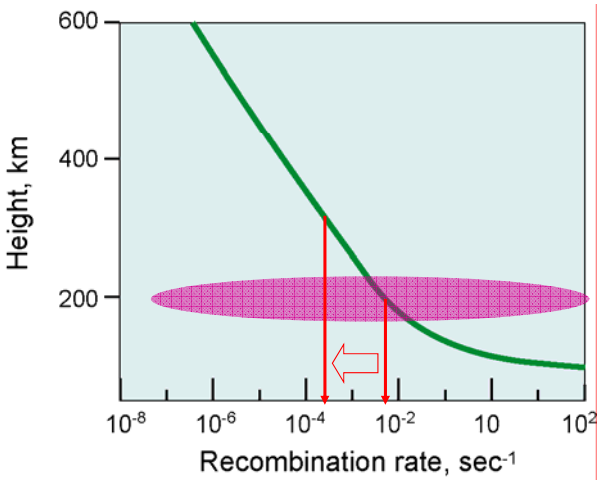


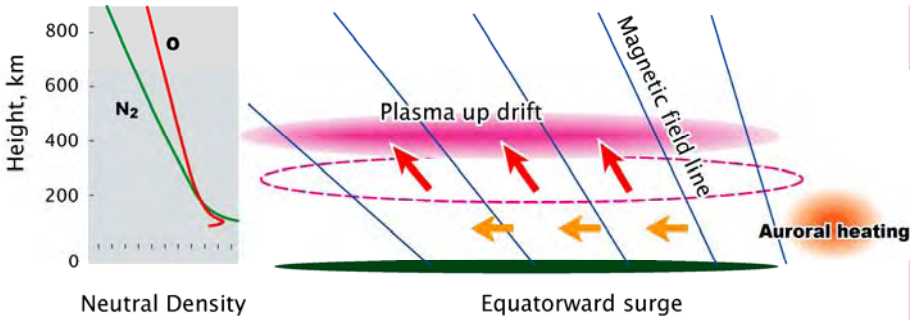
Mechanism of positive storm



Ionosphere is raised ➡ Recombination rate decreases ➡ Density increases

When equatorward surge is dominant

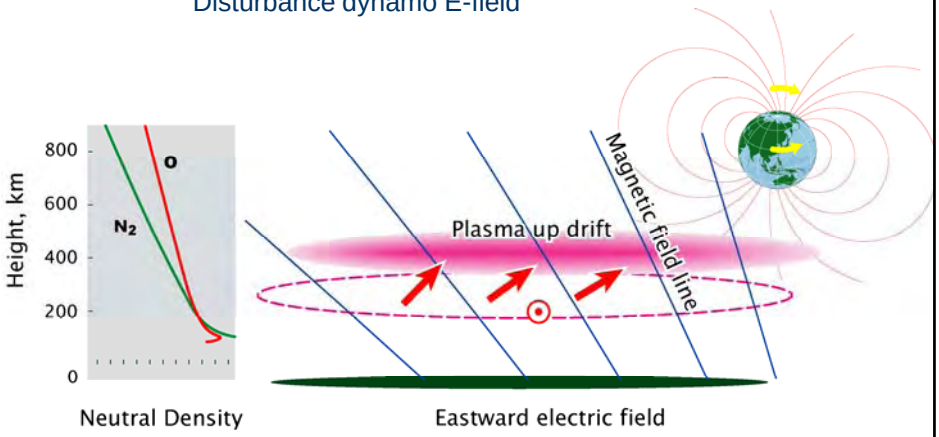
Equatorward wind disturbance with fast phase velocity reaches before the composition-changed atmosphere.



~ 600 m/sec

Another mechanism of positive storm

Prompt penetrating magnetospheric E-field
Disturbance dynamo E-field



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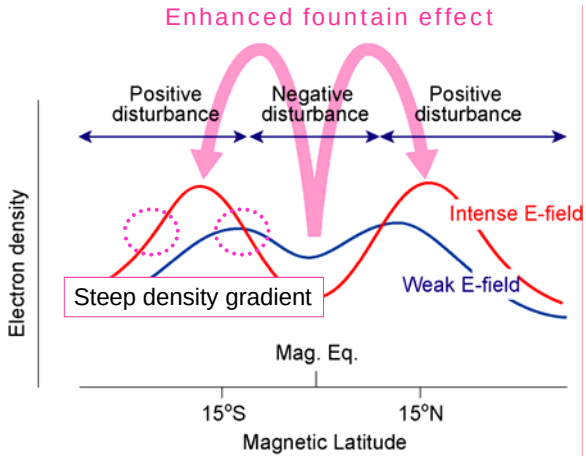

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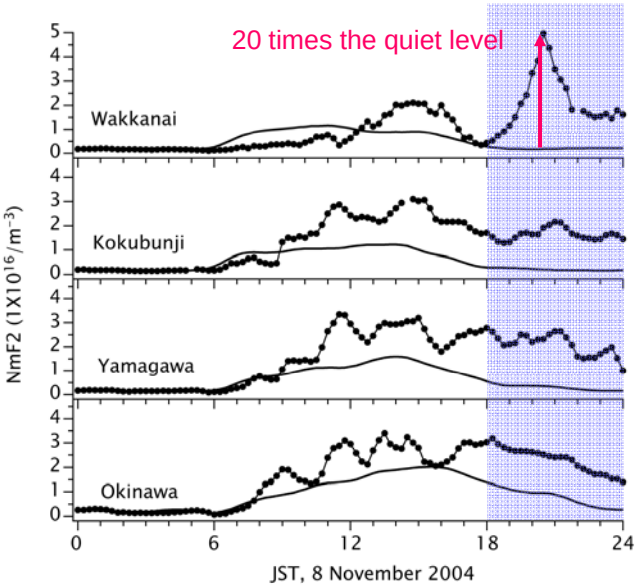
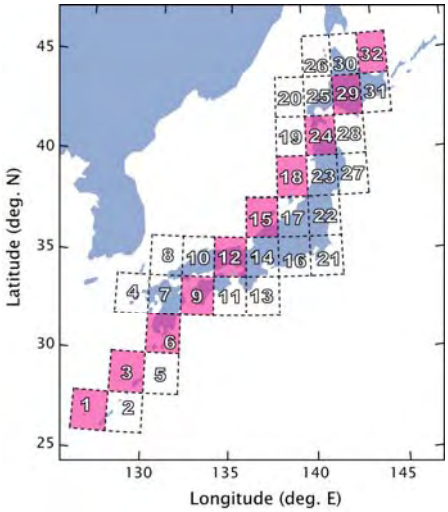
Strong positive disturbance after sunset

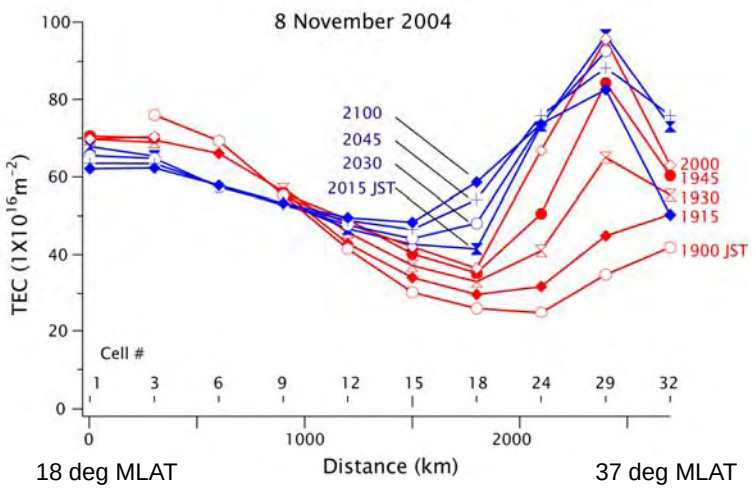


TEC variations along NE-SW line

TECs were determined over the cells at 15 min intervals



TEC variations along NE-SW line

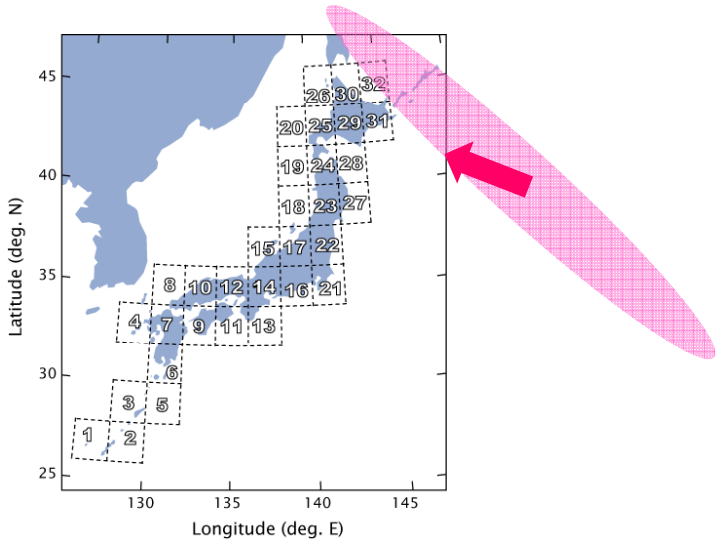


18 deg MLAT

37 deg MLAT

High-electron density stream

DMSP satellite observed large westward ion drift



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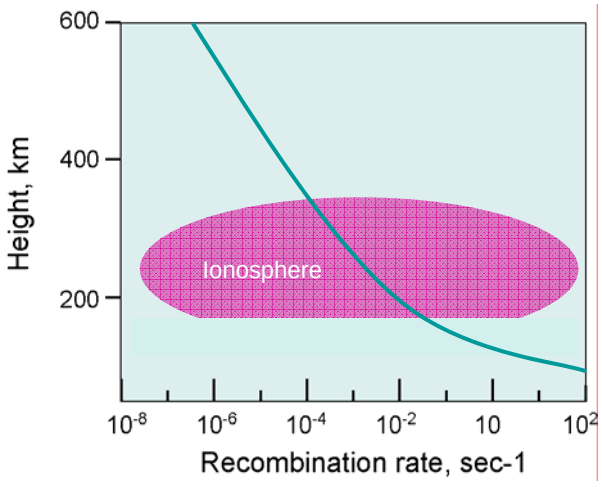
  - Negative and positive storms
  - Storm enhance density (SED)
  - **Plasma bubbles**
- Summary

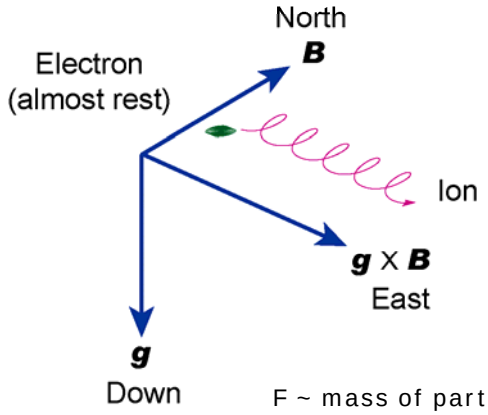
After sunset



Lower part of the ionosphere rapidly disappears after sunset because of a large recombination rate

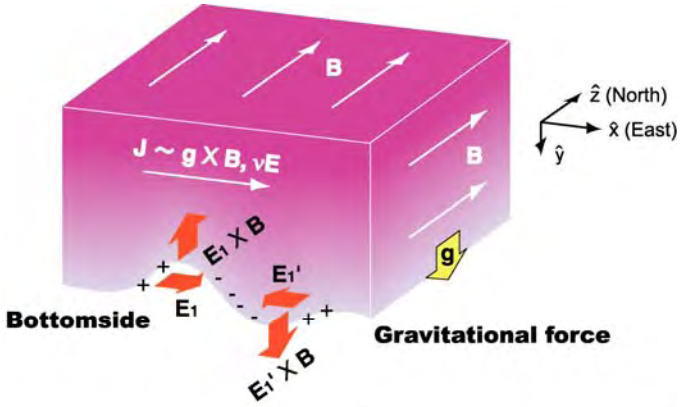
Motion of charged particles by gravity

Near the magnetic equator, B-field is horizontal and directs north
Ions drift toward East and electrons almost rest.
As a result, charge separation occurs.



F ~ mass of particle

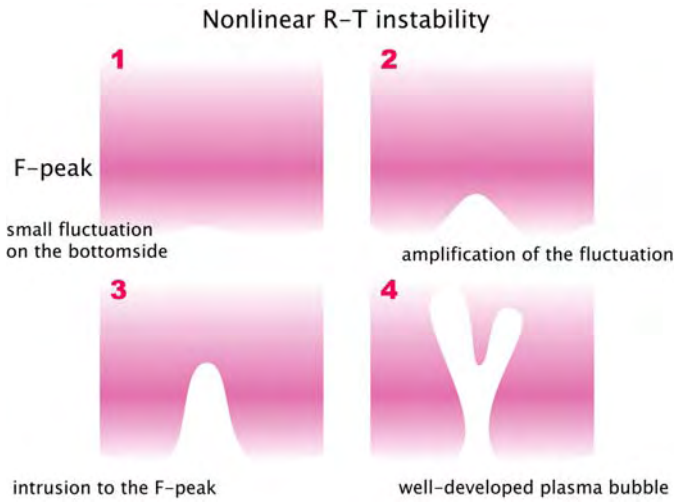
Rayleigh-Taylor instability



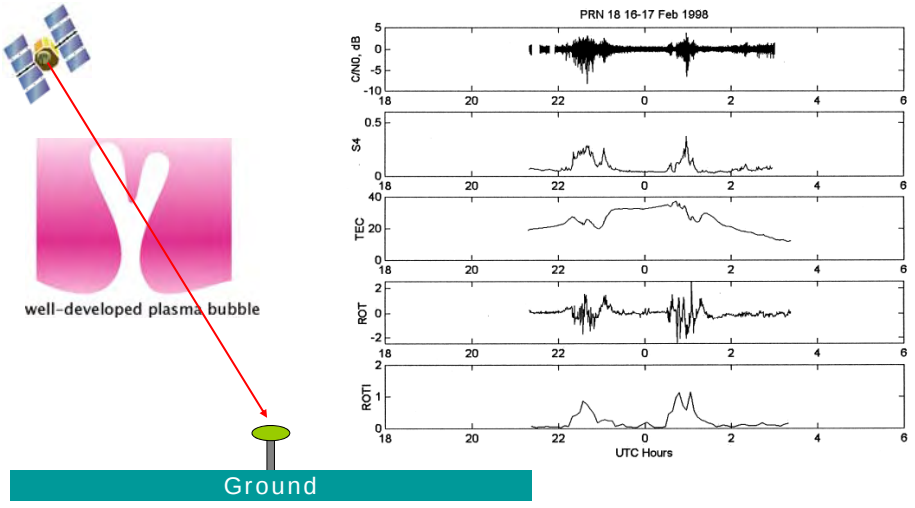
Growth rate of R-T instability

$$\gamma_{RT} = -(E_0/B + g/\nu)\cdot\nabla n/n$$

Time evolution of perturbation

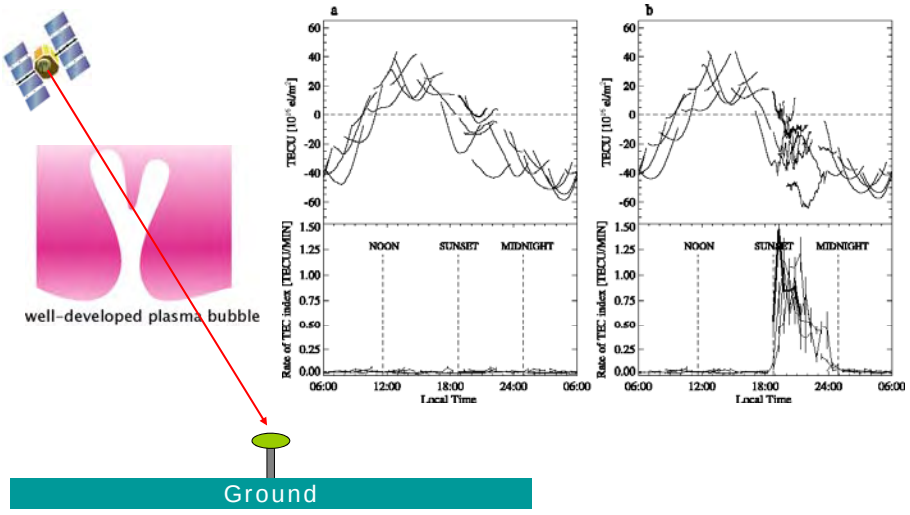


Ground observation of plasma bubble



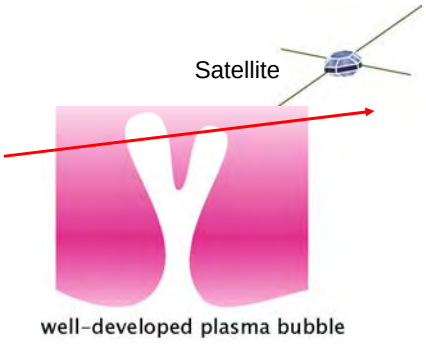
[Basu et al., JASTP 1999]

Rate of TEC change index (ROTI)

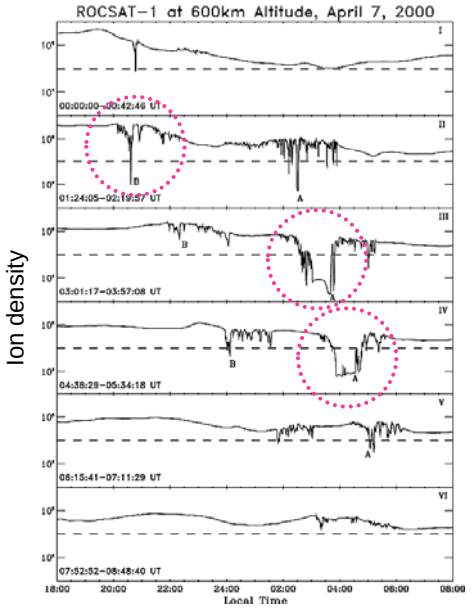


[Nishioka et al., JGR 2008]

Satellite in-situ measurements

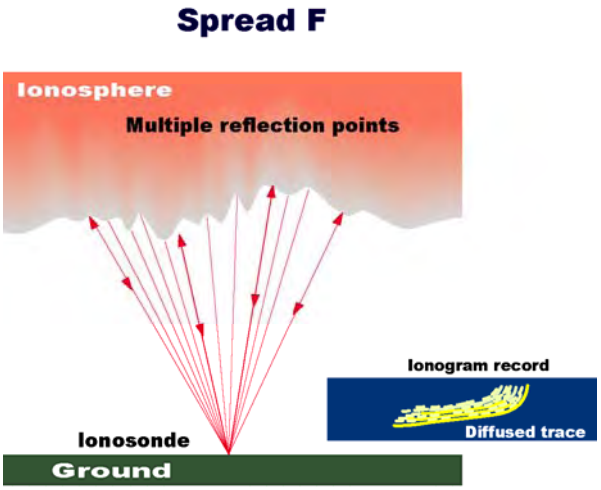


When satellite orbit crosses a bubble, density dropouts are observed

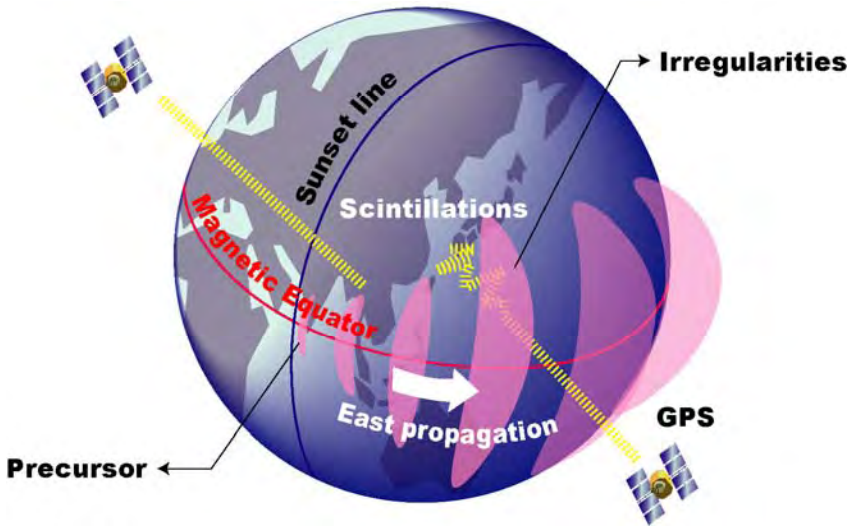


[Su et al., JGR 2002]

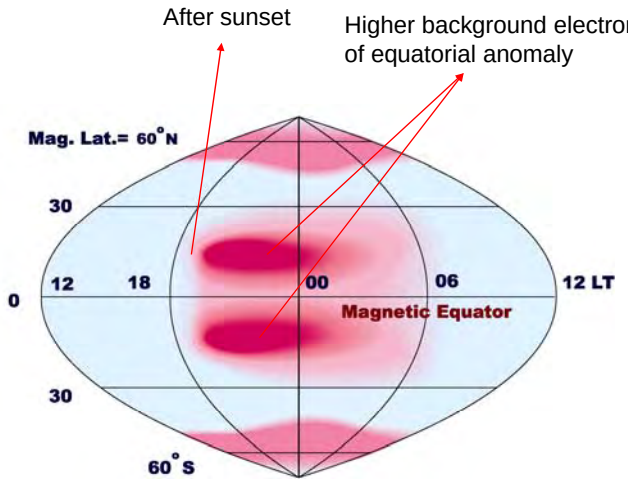
Ionosonde observation of irregularities



3-D image of plasma bubble



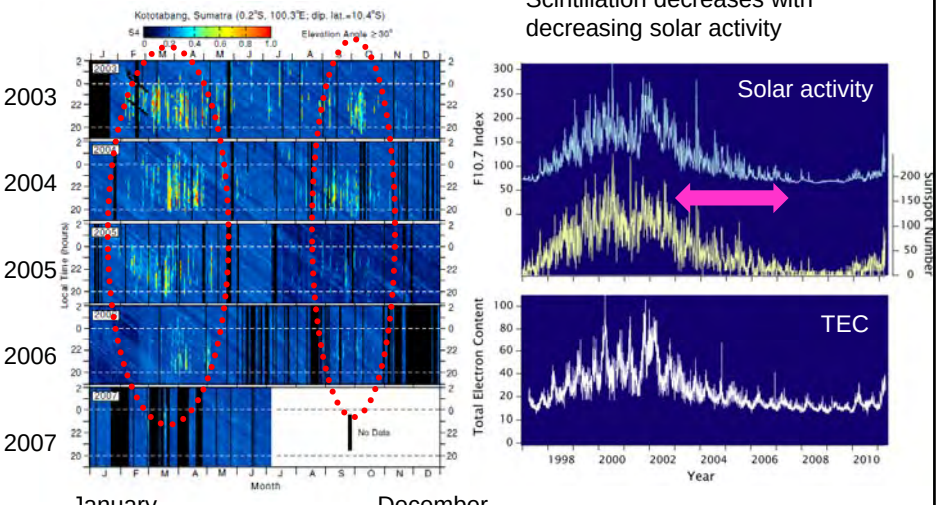
Occurrence probability of intense scintillations



There is a season of scintillation

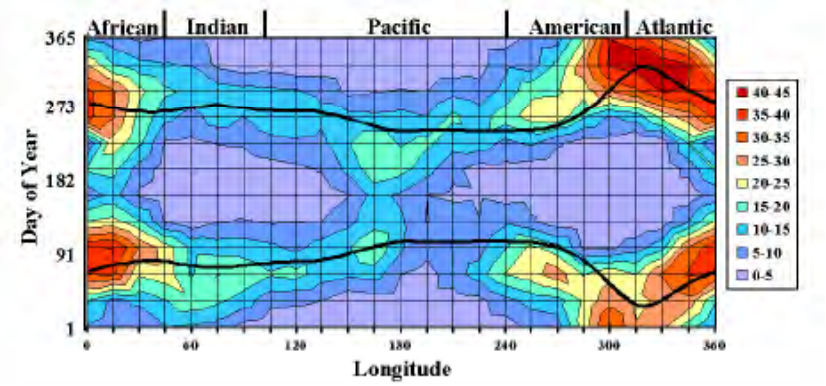
Equinox is a high season of scintillation at Asian longitudes

Scintillation decreases with decreasing solar activity



January December

Scintillation season varies with longitude



Ionospheric irregularities measured by DMSP satellites

Burke et al., Annales Geophysicae (2004) 22: 3089–3098

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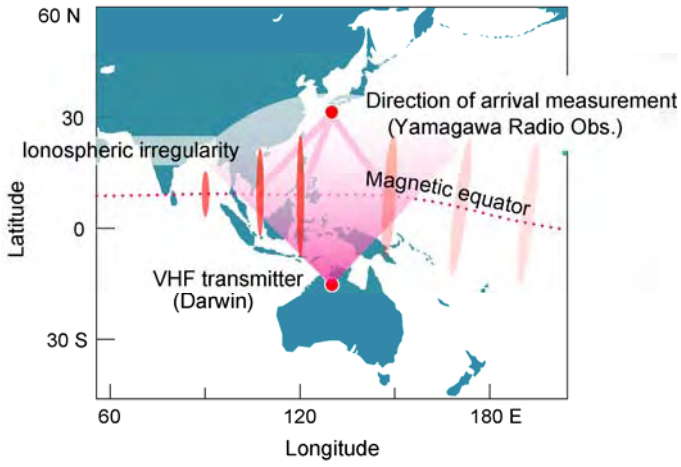
Summary

- The ionosphere is an upper atmospheric region where a fraction of particles are ionized and free electrons exist.
- GPS radio signals delay in the ionosphere depending on the concentration of the free electron.
- The ionosphere can be measured by many techniques including GPS radio waves.
- The ionosphere varies with several characteristic periods such as 11-year solar cycle, seasonal, and diurnal. Geographical distribution exhibits an equatorial anomaly.
- Large TEC enhancements and depletion called a storm sometimes occur during geomagnetic storms. Plasma bubbles are the most significant disturbances in the equatorial ionosphere.

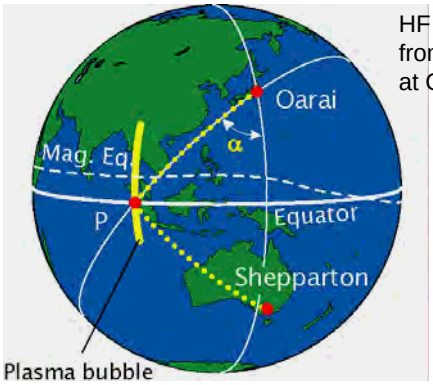
Remote detection of plasma bubbles (proposal)

VHF forward scattering by field aligned irregularities



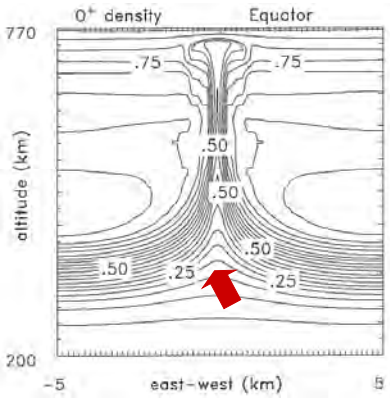
Darwin-Yamagawa are magnetic conjugate points

HF trans-equatorial observation



HF radio broadcast signal of Radio Australia from Shepparton, Australia is received at Oarai, near Tokyo in Japan.

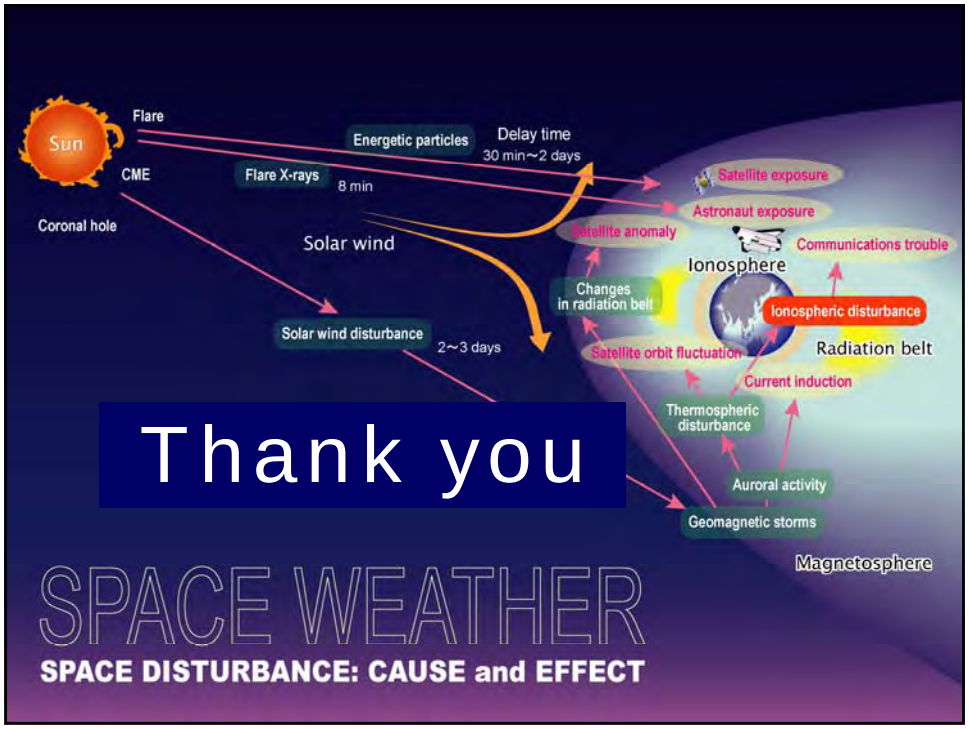
Observables: α(direction of arrival)



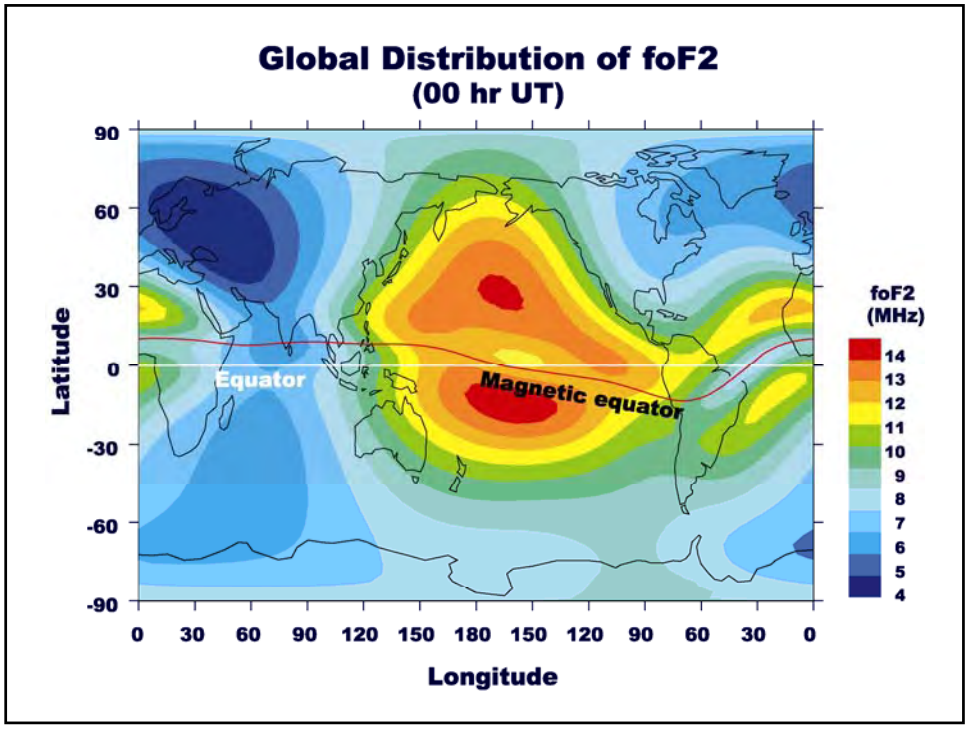
HF radio waves are reflected by the bottomside structure of plasma bubbles

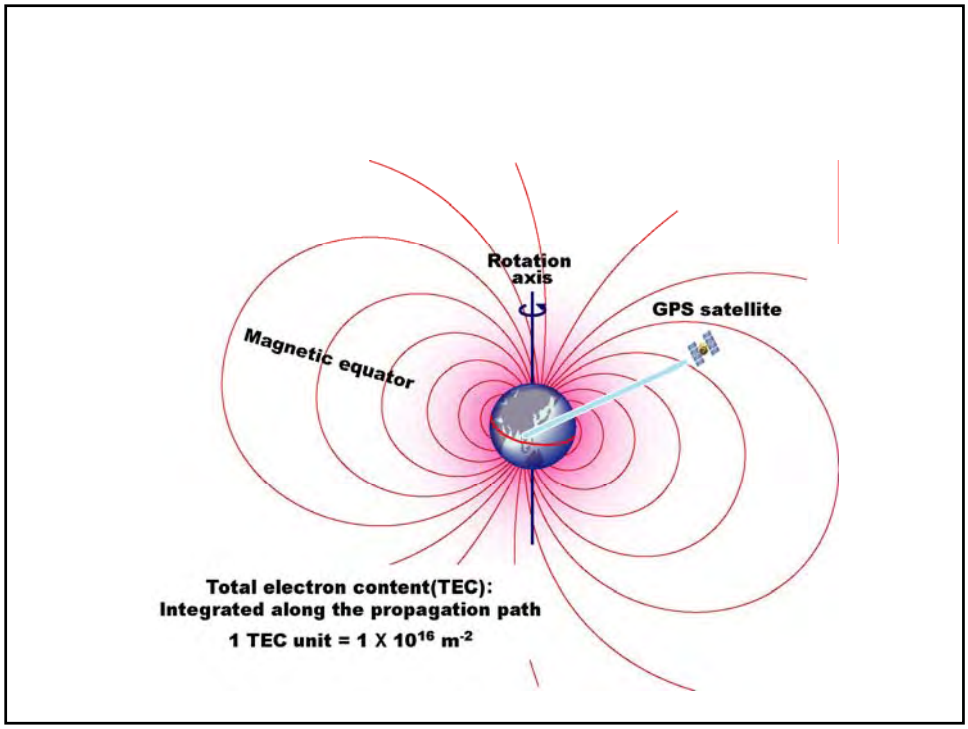
When the bubble moving eastward α decreases

[After *Keskinen et al.* (2003)]



Thank you


Global Distribution of foF2
(00 hr UT)
Latitude
90
60
30
0
-30
-60
-90
Equator
Magnetic equator
0 30 60 90 120 150 180 150 120 90 60 30 0
Longitude
foF2
(MHz)
14
13
12
11
10
9
8
7
6
5
4


Rotation
axis
GPS satellite
Magnetic equator
Total electron content(TEC):
Integrated along the propagation path
1 TEC unit = 1 X 10^16 m^-2

Strong positive disturbance after sunset