Earth Environment – Thermosphere & Ionosphere

Tobias G.W. Verhulst

STCE – Royal Meteorological Institute of Belgium

STCE Space Weather Introductory Course

RMI

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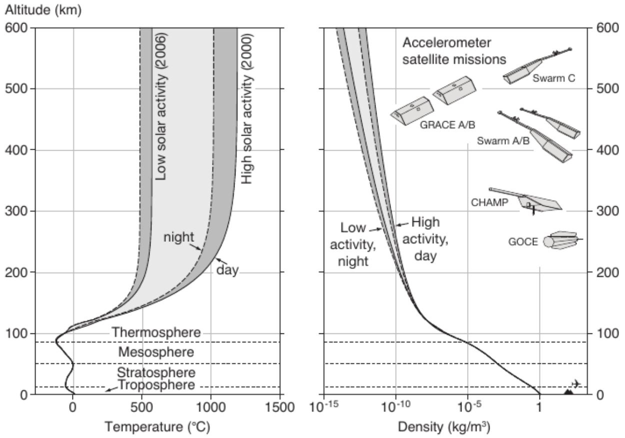
Outline

Introduction

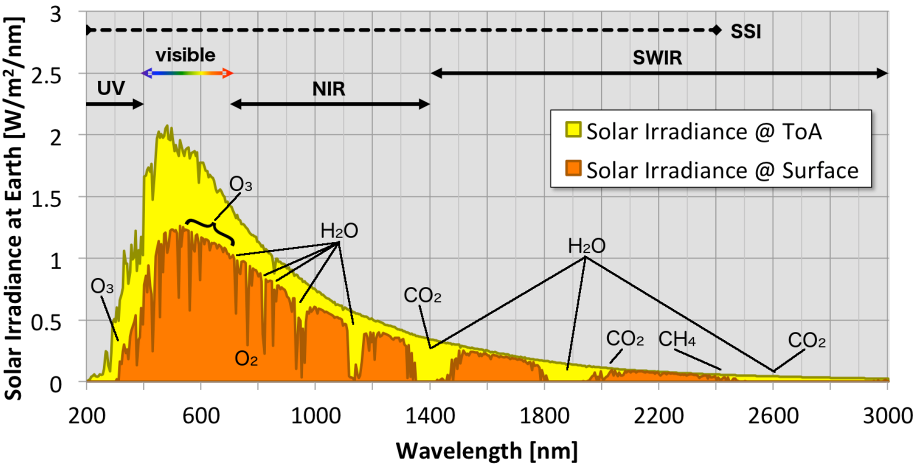
The thermosphere

The thermosphere is the atmosphere above 90 km.



Note: temperature, density, composition all change with varying irradiation.

Solar electromagnetic spectrum

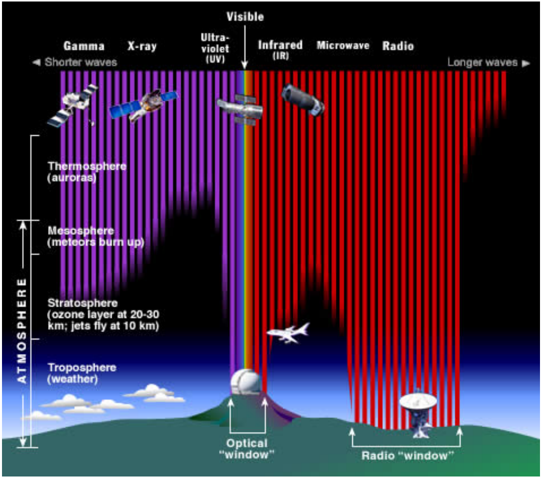


The flux of solar radiation drops of quickly at higher energies (= higher frequencies = shorter wavelengths). High energy particles can also produce ionisation.

Electromagnetic radiation penetration depth

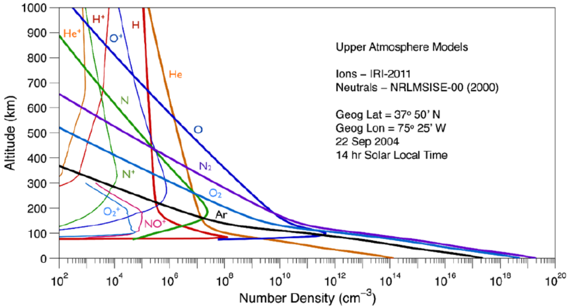
Different wavelengths penetrate the atmosphere to different altitudes.

For the ionising frequencies: higher energy means penetration to lower altitudes.



Thermospheric composition

The thermosphere contains mostly atomic gases (produced by photodissociation) rather than molecular ones (O_2, N_2, CO_2,...). Most important are O, H, and He.



Question:

The lower atmosphere is mostly N_2, why is there so little N in the thermosphere?

Ionisation and recombination

The primary production of ionisation reaction: $O + \hbar\nu \longrightarrow O^+ + e^-$, where the photon is EUV or X-ray.

Most important fact of aeronomy

Ionisation of O is not easily (directly) reversible:

$$O + \hbar\nu \underset{\text{very slow}}{\overset{\text{very fast}}{\rightleftharpoons}} O^+ + e^-$$

Instead, recombination goes like this (for example):

$$O^+ + N_2 + e^- \longrightarrow NO^+ + N + e^- \longrightarrow NO + N + \text{dissipate energy}$$

Thus, *recombination rate is primarily determined by density of surrounding neutral gas.*

Summary

1. Thermosphere mostly composed of atomic O, produced by photodissociation.
2. Solar EUV and X-rays ionise part of the O, creating free electrons.
3. Once produced, O^+ does not easily recombine into neutral O unless a catalyst is available.

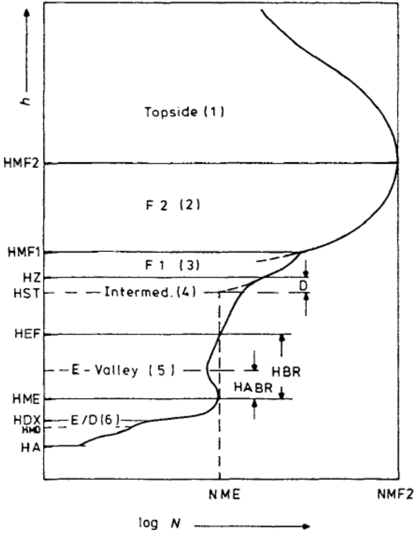
The end this section.

Questions so far?

Mid-latitude ionosphere

Ionisation & distribution of free electrons

Electron distribution at mid-latitudes (roughly 30°–60°) has a typical layered structure.

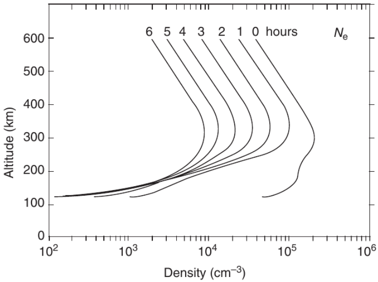


- Equilibrium between photoionisation and recombination (driven by neutral density): maximum free electron density at some altitude.
- Actually to main maxima: *F* layer above 150 km due to EUV, *E* layer around 100 km due to X-rays.
- Hard X-rays can produce an additional, lower *D* layer.

Recombination

During the night, ionisation disappears due to recombination (note the logarithmic density scale).

Recombination rate depends strongly on *neutral* density, thus: higher at lower altitude.



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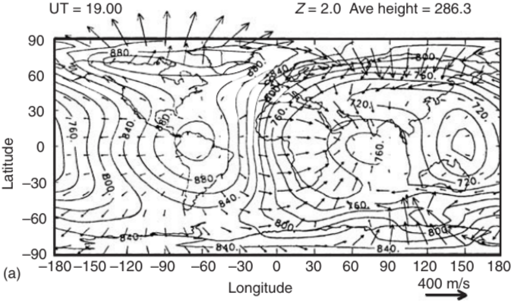
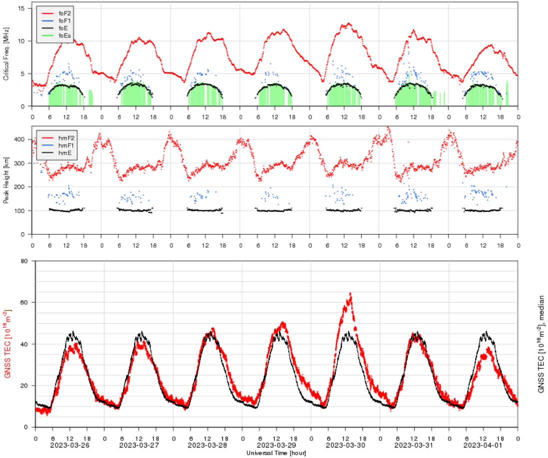


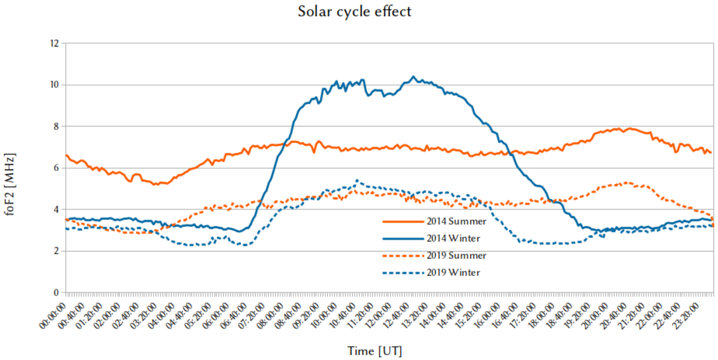
The higher F_2 layer is further maintained during night by plasma transport from the dayside, driven by solar heating of the thermosphere (horizontal drift across **B** also creates upward flow).

Diurnal variations



Peak densities and heights of the layers, and total electron content. Main features: *foF*$_2$ and *vTEC* are maximal during day, minimal at night; *hmF*$_2$ is highest in the morning hours; *E* and *F*$_1$ layers seen only during the day.

Seasonal and solar cycle dependencies



Solar irradiance also varies with season and solar cycle. Mid-latitude seasonal anomaly: foF_2 in winter larger than in summer.

Question:

What would cause ionisation to be higher in winter than in summer?

Summary

1. The (mid-latitude) ionosphere is stratified into layers: F_2, F_1, E, D.
2. The lower layers are formed by simple ionisation/recombination equilibria.
3. The F_2 layer is produced by plasma transport, and persists through the night.
4. Solar irradiance is the main factor influencing the ionosphere, but plasma transport and chemistry are also important.

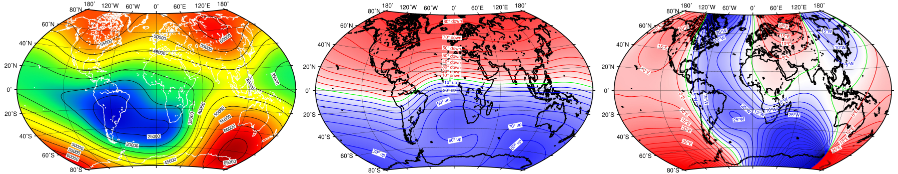
The end of this section.

Questions so far?

Low- and high-latitude ionosphere

The global geomagnetic field

Besides solar irradiation, the ionosphere is strongly influenced by the geomagnetic field.



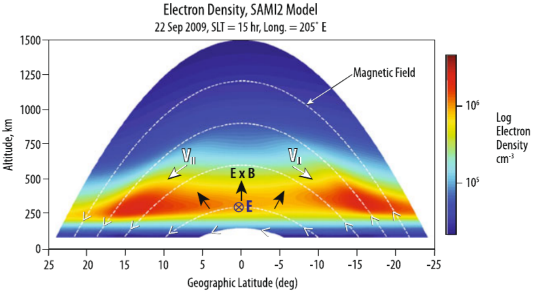
The best fitting dipole for the geomagnetic field is tilted from the rotational axis, but it is also laterally displaced by about 700 km.

1. Latitudinal variation in strength and inclination.
2. Orientation of neutral winds to the magnetic field varies a lot.
3. Regions of weaker/stronger magnetic field at the same latitude.

The Equatorial Ionisation Anomaly

The “Equatorial Ionisation Anomaly” is a permanent feature of the day-time low latitude ionosphere.

1. Thermospheric wind creates dynamo **E**, eastward during day-time.
2. This causes **E** $\times$ **B** drift upwards.
3. This plasma then diffuses along the filed lines away from the equator.



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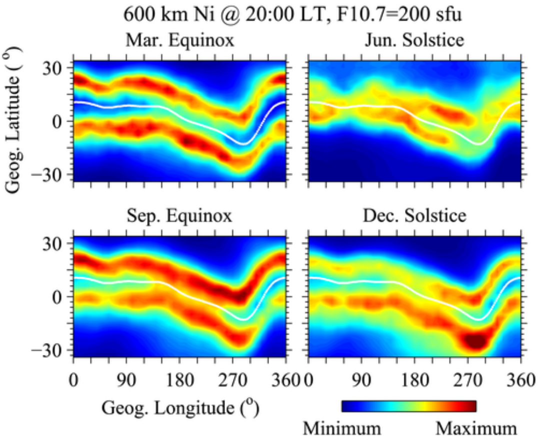
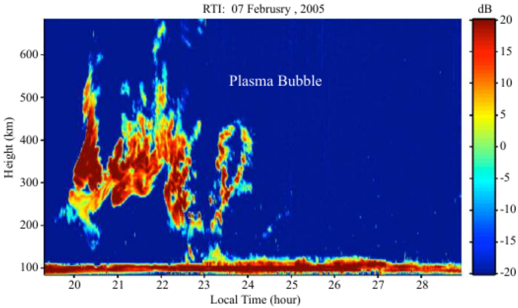
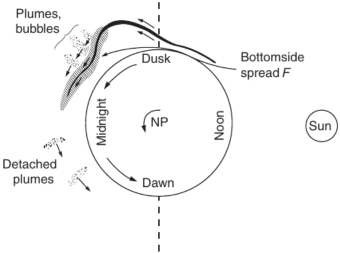


There is also some longitudinal structure & seasonal variation at low latitudes; the most important is related to the South-Atlantic anomaly.

Plasma bubbles

Plasma bubbles are a regular feature of the equatorial night-time ionosphere (and a source of spread-*F* and scintillation).

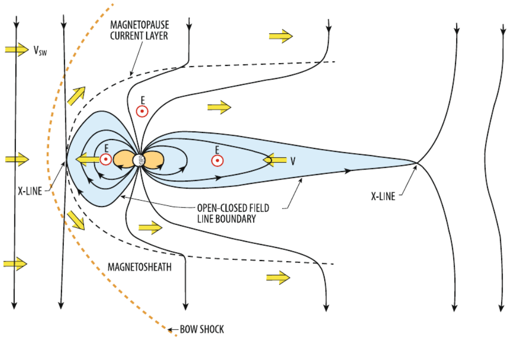




They generally form below hmF_2 and rise to over 700 km, while drifting eastward.

High latitude ionosphere

The high-latitude ionosphere is the most complex region, comprising two very different regions: auroral oval and polar cap.



In the *polar cap*, magnetic field lines are open, connected to the interplanetary field. The *auroral oval* is the transition region to closed field lines.

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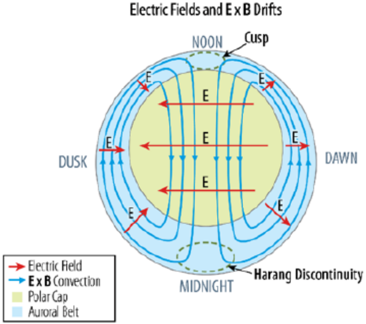

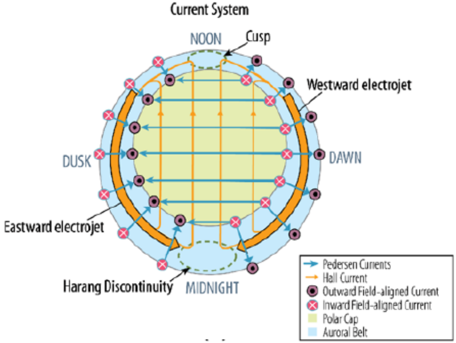

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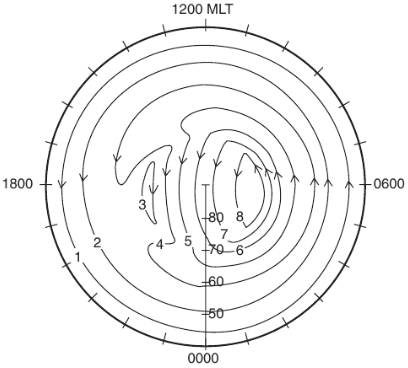
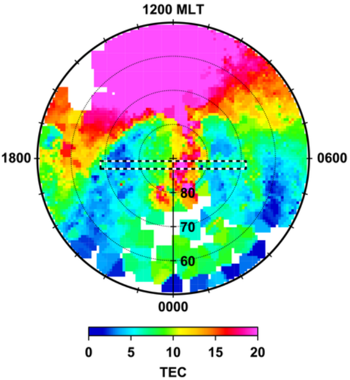
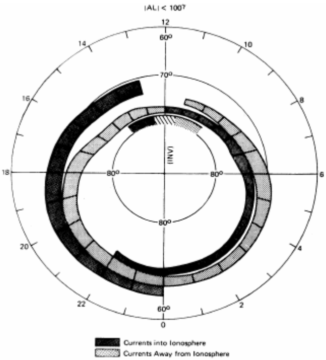
Auroral oval and polar cap

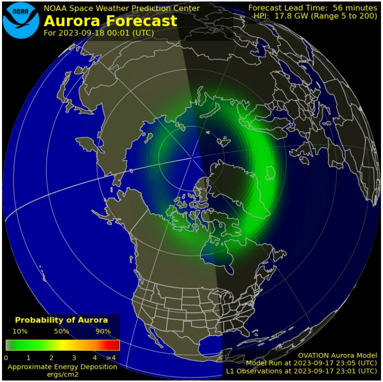




Polar cap: Plasma flow from noon to midnight over the pole, return around the edges (driven by neutral wind, Earth rotation & interplanetary field orientation).

Auroral oval and polar cap



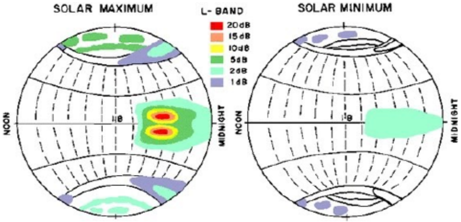


Polar cap: Plasma flow from noon to midnight over the pole, return around the edges (driven by neutral wind, Earth rotation & interplanetary field orientation).

Auroral oval: Two regions, one with inflow from, one with outflow to the magnetotail (directly influenced by magnetospheric storms).

Scintillation

Scintillation is an important issue for transionospheric VHF/UHF signals.



Global variation of amplitude scintillation fades at L band (after Basu et al. 1988a, b, colored by A.W. Wernik)

Although the effect on radio waves is similar, the equatorial, auroral, and polar-cap scintillation have different physical origins:

- In the equatorial region: plasma bubbles (decreased ionisation).
- In the auroral regions and polar cap: arcs and patches of increased ionisation.

Summary

1. The low-latitude ionosphere is dominated by a plasma fountain effect producing the "Equatorial Ionisation Anomaly."
2. The South-Atlantic anomaly region is due to the peculiar configuration of the geomagnetic field.
3. High latitude, two different regions:
    1. polar cap (open field lines),
    2. auroral oval (connected to magnetotail).
4. High latitude ionosphere is often severally disturbed.
5. Even in quiet time, scintillation occurs due to (1) equatorial plasma bubbles, (2) polar cap patches, (3) auroral oval irregularities.

The end of this section.

Questions so far?

Ionospheric disturbances

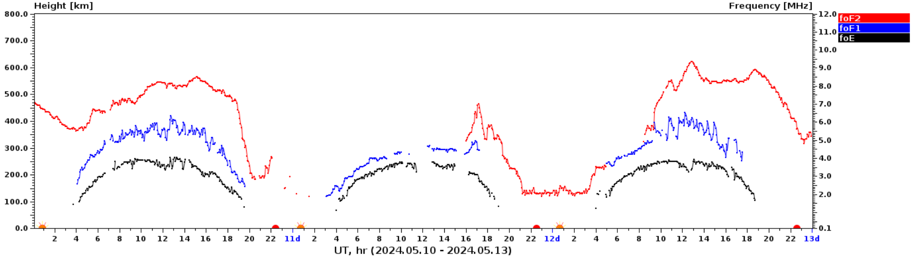
Geomagnetic/ionospheric storms

The most significant disturbances to the ionosphere result from solar events (CMEs, CIRs), propagating through the solar wind and interacting with the magnetosphere.

1. Energy injected into the ionosphere, mainly at high latitude.
2. As a result, the auroral oval expands.
3. This causes large scale movement of plasma towards the equator.
4. Drift along the magnetic field lines cause the ionosphere to move up, which can increase electron density ("positive storm phase").
5. Finally, upwelling of N_2 causes increased recombination, leading to a depletion of ionisation ("negative storm phase").

The negative phase of a storm is always seen, and lasts for a few days. The positive phase is not always present (this depends among others things on the local time at storm onset).

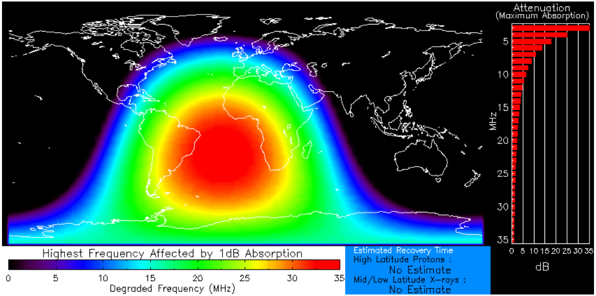
Geomagnetic storm: example



F_2-, F_1-, and E-layer peak densities after the $K_p = 9$ storm of 2024–05–11 in mid-latitude ionosphere (DB049 ionosonde, Belgium).

Solar flare effect

Hard X-rays can penetrate the thermosphere to altitudes in the *D*-region.
The sun only emits significant intensity at these wavelengths during major flares.
The absorption in this case is most severe around the sub-solar point.



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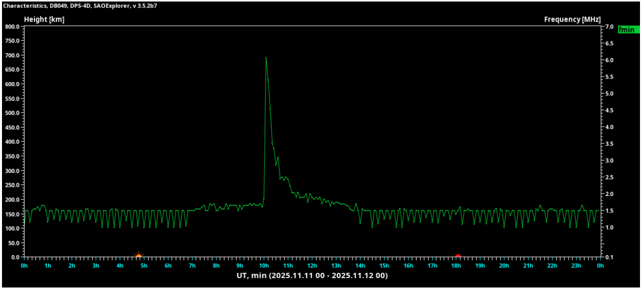
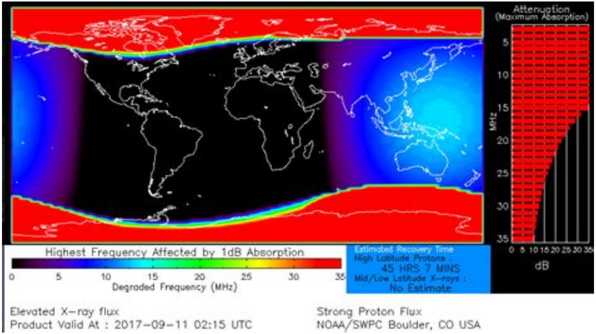


Solar flare effects usually last in the order of hours and have a predictable evolution.

Effect of solar & auroral energetic particles

Low-altitude ionisation can also be produced by solar energetic particles (mostly high-energy protons), coming in from the solar wind along open field-lines.



These events cause severe absorption in the polar & auroral region and often last longer than flares, but strictly limited to the area of open field lines.

Summary

1. Geomagnetic storms affect ionosphere via the auroral region, then propagating to lower latitudes.
   - Strong depletion of ionisation due to neutral gas upwelling, possibly lasting a few days.
   - Sometimes also an enhancement of ionisation at storm unset.
   - Expansion of auroral oval and increase of high latitude scintillation.
2. Different sources of absorption events: (1) X-ray flares, (2) particle impact from solar events (polar cap) or magnetotail (auroral oval).
3. In general, the high latitudes suffer most disturbances, the mid-latitudes the least.
4. Most types of disturbances are more common and more severe at high solar activity.

The end!

Questions?

More details: R.E. Pfaff (2012): The Near-Earth Plasma Environment, *Space Sci. Rev.* **168**, 23–112, doi:10.1007/s11214-012-9872-6.