Space Weather
Lecture 9: Ionosphere

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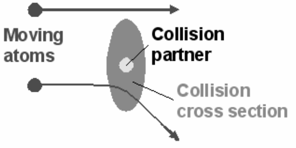
Ionosphere formation

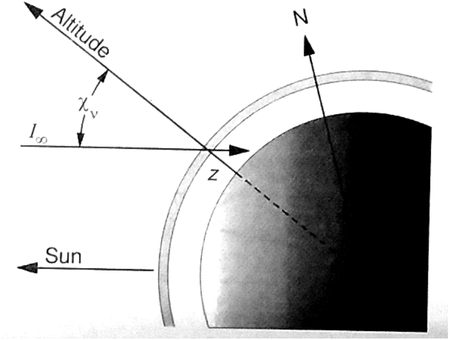
- Ionosphere is the transition region between fully ionized magnetospheric plasma and neutral atmosphere.
- It is a mixture of ionized and neutral particles: partially ionized plasma.
- Therefore, Coulomb and neutral collisions may contribute to electrical conductivity.

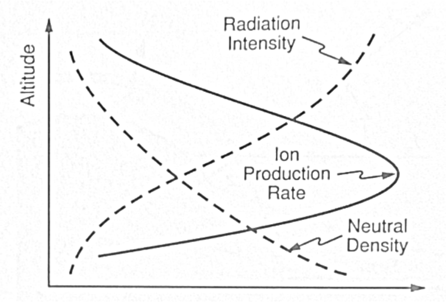


- Fully ionized plasmas: magnetosphere, solar wind; partially ionized plasma: Sun's photosphere, chromosphere, ionosphere
- There are two main sources of ionization: ultraviolet radiation from the Sun and precipitation of energetic particles from the magnetosphere into the atmosphere.

Solar Ultraviolet (UV) Ionization

- The photoionization layer in the ionosphere exhibits a strong dependence on geographic latitude, time of day and season.

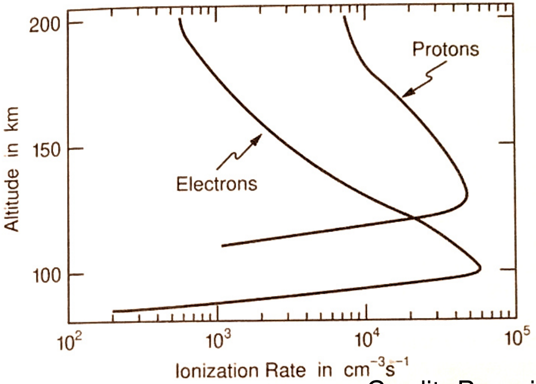




Credit: Baumjohann+Treumann

Ionization by Energetic Particles

- Dominates at high magnetic latitudes in the auroral zone, where photoionization becomes less important
- During nighttime, when photoionization ceases, ionization due to particle impact can maintain the ionosphere

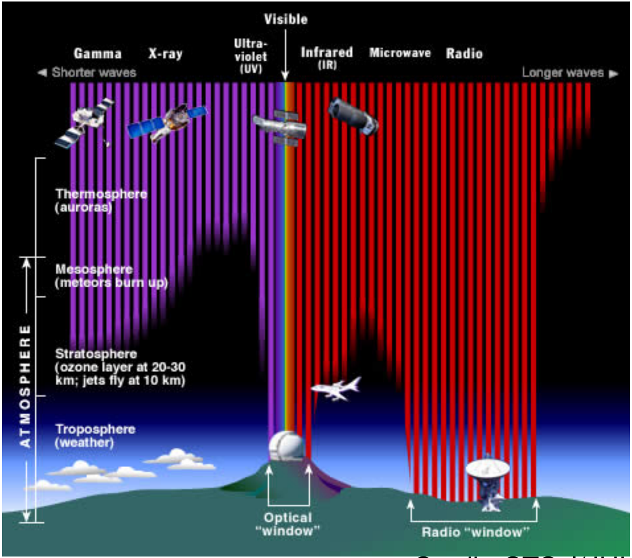


Credit: Baumjohann+Treumann

Recombination and Attachment

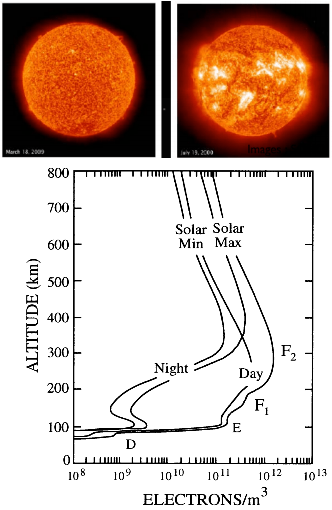
- The production of ionization in the ionosphere either by solar UV radiation or by energetic particles would, if it continued endlessly, lead to full ionization of the upper atmosphere.
- In reality two processes counteract the ionization:
  1. Recombination of ions and electrons to reform neutral atoms
  2. Attachment of electrons at neutral atoms or molecules to form negative ions

Penetration of electro-magnetic radiation and altitude



Credit: STScI/JHU/NASA

Ionospheric layers: from ∼60 to ∼1000 km

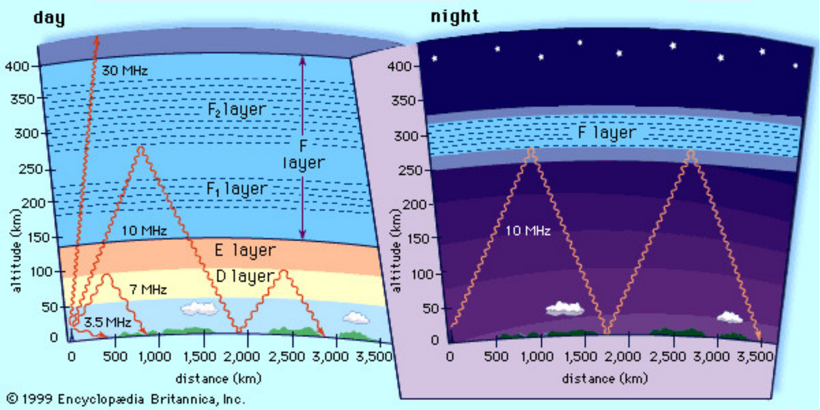


Credit: Paschmann+02

- D-layer is connected with the most energetic precipitation.
- E-layer contains mainly O_2^+ and NO^+ ions produced by UV radiation (100–150 nm) and solar X-rays (1–10 nm).
- F1-layer is composed of mainly O^+ produced by UV radiation in the range from about 17 to 91 nm.
- F2-layer is also composed of O^+, formation is complicated: photochemical processes, vertical movement due to neutral drag and magnetospheric effects.

F-layer is the most important region for long distance HF radio communications.

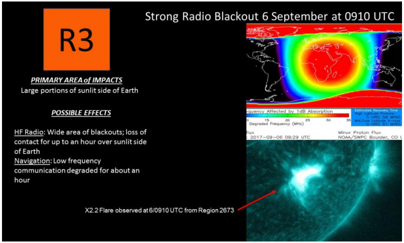
Ionospheric layers and HF radio communication

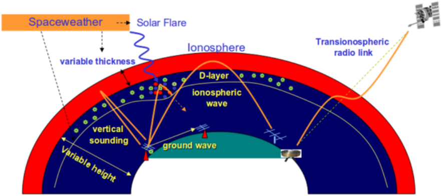


Space weather effects: Associated with solar flare

A Space Weather event: Sept 6, 2017

- The sudden outburst of electromagnetic energy travels at the speed of light. The sunlit side of Earth is exposed. The increased level of X-ray and extreme ultraviolet (EUV) radiation results in ionization.
- The D-layer becomes more dense. This can cause HF radio signals to become degraded or completely absorbed.

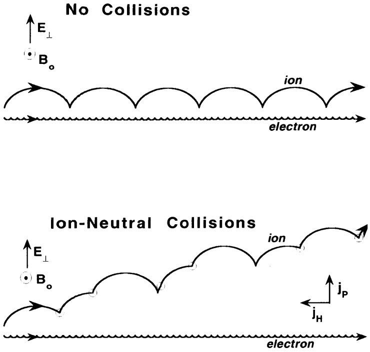




Ionospheric conductivity

- The presence of free charges in the ionosphere results in a conductivity which is anisotropic due to the effects of the magnetic field and collisions.
- The three current components are:

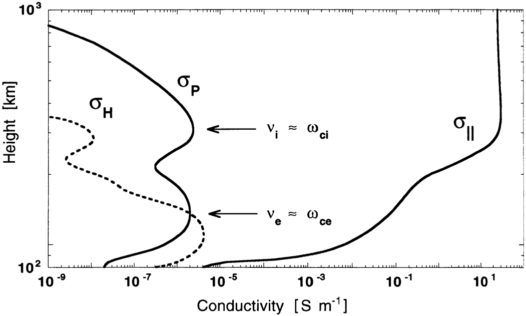
1. the field-aligned (parallel) current $\mathbf{j}_{\parallel} = \sigma_{\parallel} \mathbf{E}_{\parallel}$
2. the Pedersen current $\mathbf{j_P} = \sigma_P \mathbf{E}_{\perp}$ flowing parallel to the transverse electric field $\mathbf{E}_{\perp}$
3. the Hall current $\mathbf{j_H} = \sigma_H \hat{\mathbf{b}} \times \mathbf{E}$ which flows transverse to both the magnetic and electric fields



Credit: Menk&Waters + Paschmann+02

Ionospheric conductivity

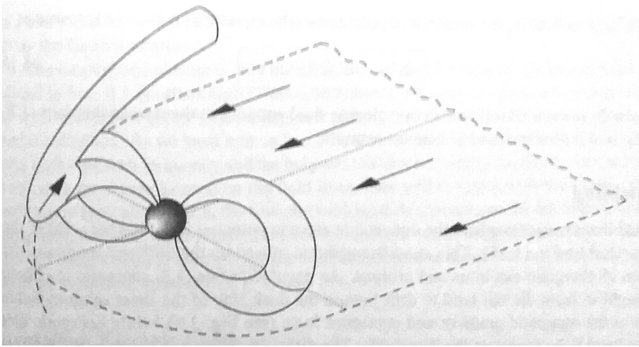
The conductivities are defined as $\sigma_{\parallel} = \sum_{\mathrm{s}} \frac{n_{\mathrm{s}} q_{\mathrm{s}}^2}{m_{\mathrm{s}} \nu_{\mathrm{s}}}$, $\sigma_P = \sum_{\mathrm{s}} \frac{n_s q_{\mathrm{s}}^2}{m_{\mathrm{s}}} \frac{\nu_{\mathrm{s}}}{\nu_{\mathrm{s}}^2 + \omega_{\mathrm{cs}}^2}$ and $\sigma_H = -\sum_{\mathrm{s}} \frac{n_{\mathrm{s}} q_{\mathrm{s}}^2}{m_{\mathrm{s}}} \frac{\omega_{\mathrm{cs}}}{\nu_{\mathrm{s}}^2 + \omega_{\mathrm{cs}}^2}$, where $n_{\mathrm{s}}, q_{\mathrm{s}}, m_{\mathrm{s}}$ and ν_{s} indicate density, charge, mass and particle-neutral collision frequency, respectively, of particles of species s, and $\omega_{\mathrm{cs}} = q_{\mathrm{s}} B / m$ is the gyrofrequency of species s.



Credit: Paschmann+02

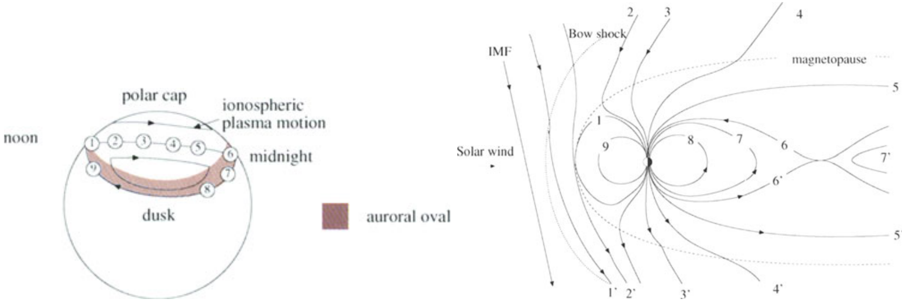
Plasma Convection

- Flux tube and plasma convection caused by magnetic merging



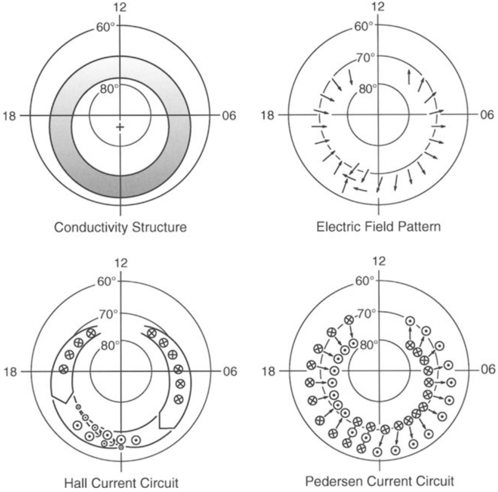
Credit: Baumjohann+Treumann

Reflection of the convection in the ionosphere



Credit: Paschmann+02, Kivelson&Russell

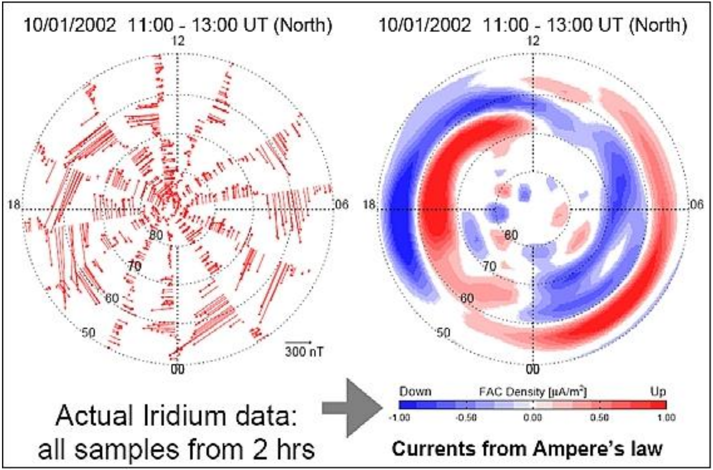
Currents in the ionosphere



Credit: Baumjohann+Treumann

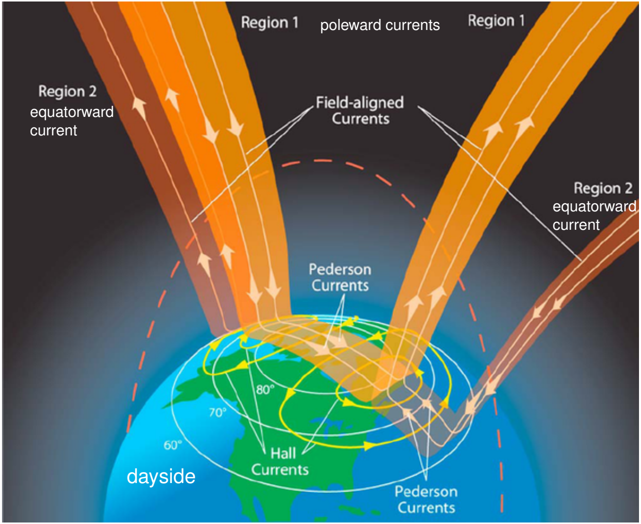
Currents in the ionosphere

AMPERE (Active Magnetosphere and Planetary Electrodynamics Response Experiment) observations



Credit: JHU/APL

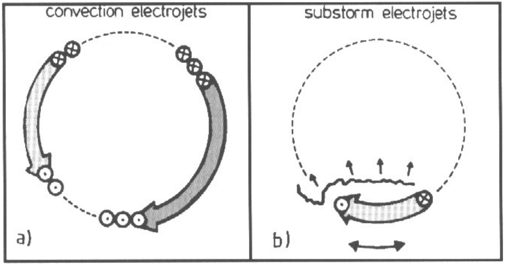
Ionosphere-Magnetosphere coupling



Le+2010; also Wikipedia

Currents during substorm

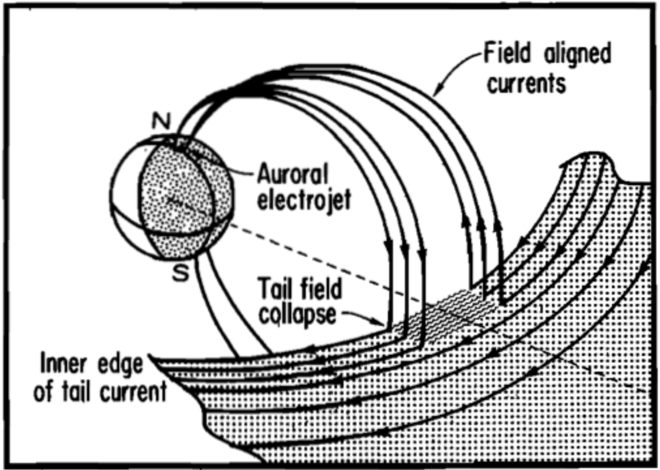
- Left side: convection electric field during substorm strengthens convection auroral electrojets (Hall currents, travel around the E region)
- Right side: substorm electrojet is formed by the substorm current wedge (Hall current)
- The strength of substorm electrojet is mainly determined by increase in ionospheric conductance because of strong particle precipitation.



Credit: Cravens, 1997

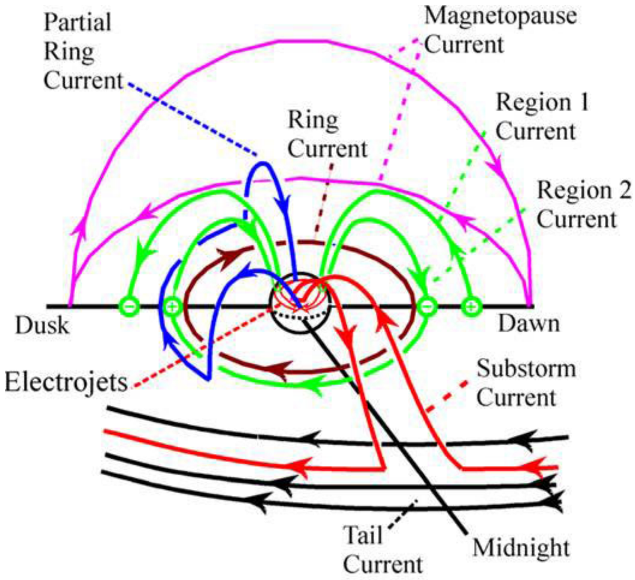
Substorm Current Wedge

- The substorm current wedge diverts part of the neutral sheet current along magnetic field lines through the ionosphere

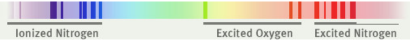


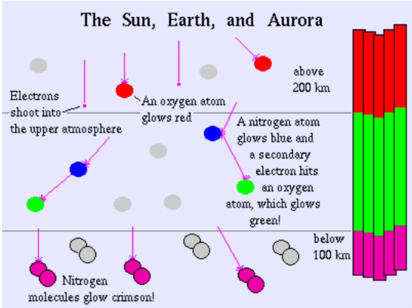
McPherron&Chu 16

Ionosphere-Magnetosphere coupling

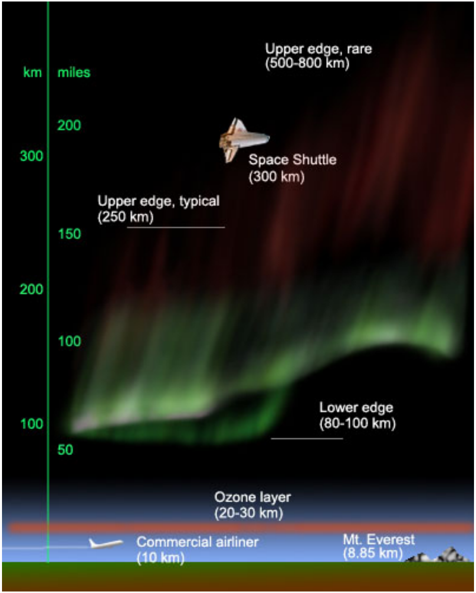


Aurora: colors





Collision of particles at different energies with ionospheric atoms lead to emissions of different colors

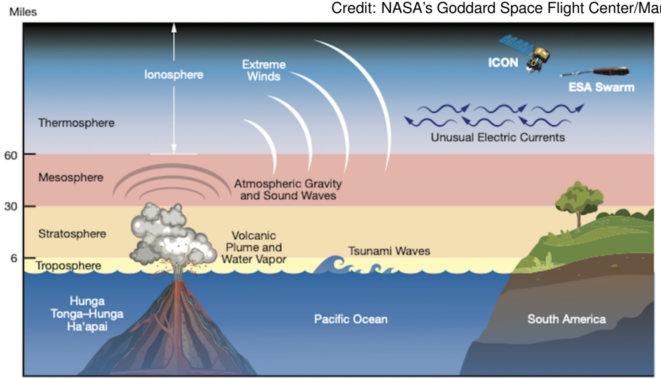


Aurora: forms

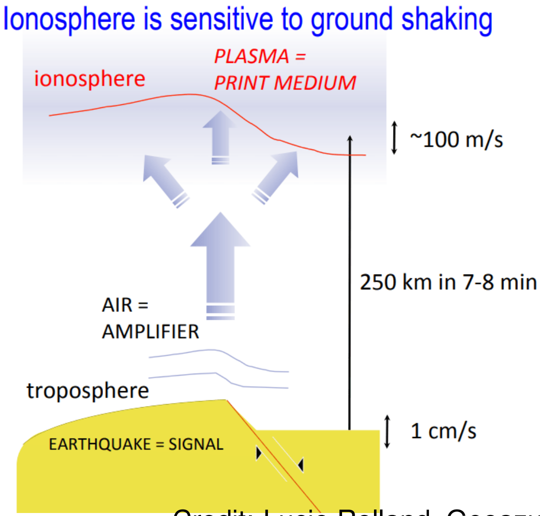
Hunga Tonga-Hunga Ha’apai eruption on 15/01/2022 affects space weather

- The explosion created large pressure disturbances in the atmosphere, leading to strong winds which affected electric currents.
- The equatorial electrojet surged to five times its normal peak power and dramatically flipped direction, flowing westward for a short period (as due to the ring current).
- A strong equatorial electrojet is associated with redistribution of material in the ionosphere. This can disrupt GPS and radio signals that are transmitted through the region.

Credit: NASA’s Goddard Space Flight Center/Mary Pat Hrybyk-Keith



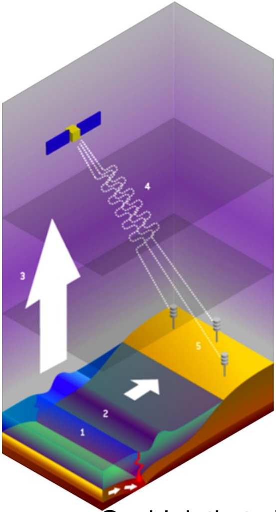
An earthquake (EQ) disturbs the surrounding atmosphere = propagating upward acoustic and gravity waves



Credit: Lucie Rolland, Geoazur/OCA/UCA

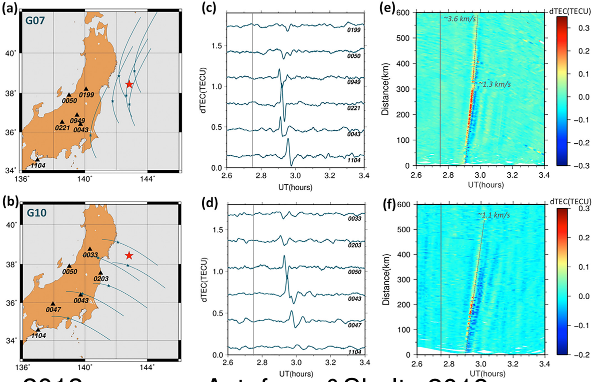
The electromagnetic waves from GPS satellites are perturbed by ionosphere and can image the EQ waves

The method can be used as independent or complementary one for near real-time tsunami warning systems.



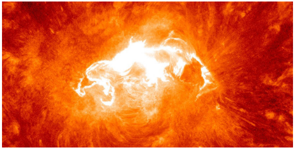
Occhipinti et al., 2013

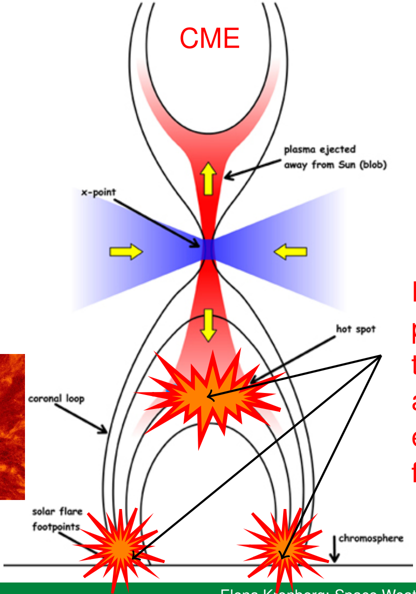
Mw7.4 Sanriku-oki earthquake of 9 March 2011



Astafyeva&Shults 2018

Chromosphere and Ionosphere: anology





Partcile precipitation triggers ionization and release of energy → Solar flare

Credit: SSL Berkely

Summary

- The ionosphere is strongly affected by the dynamics of the Sun and particle precipitation in the atmosphere.
- The magnetosphere and ionosphere are coupled through the motion of particles along field lines producing field-aligned currents.
- These currents characterize the location of auroras.
- Intense Hall currents result in auroral electrojets that flow toward midnight around the auroral ovals (lead to irregular variations of the ground magnetic field on scales of seconds to days).
- These currents lead to geomagnetically induced currents which may disturb, e.g., work of power grids...
- The ionospheric dynamics can also be affected by the earthquakes, volcanos and be used for near-real time tsunami warning.

Literature

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- M. Kivelson and C. Russell, Introduction to Space Physics, 1995
- A. Brekke, Physics of the Upper Polar Atmosphere, 2013
- G. Paschmann, S. Haaland and R. Treumann, Auroral Plasma Physics, 2002
- F. Menk and C. Waters, Magnetoseismology: Ground-based remote sensing of Earth's magnetosphere, 2013