# Space Weather
# Lecture 9: Ionosphere

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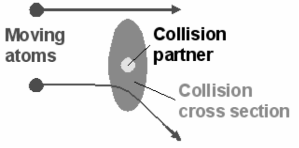
# Some history

- In 1839, Carl Friedrich Gauss speculated that an electrically conducting region of the atmosphere could account for observed variations of Earth's magnetic field.
- The name "ionosphere" was formally defined in 1950 by a committee of the Institute of Radio Engineers as "the part of the Earth's upper atmosphere where ions and electrons are present in quantities sufficient to affect the propagation of radio waves."

# Ionosphere formation

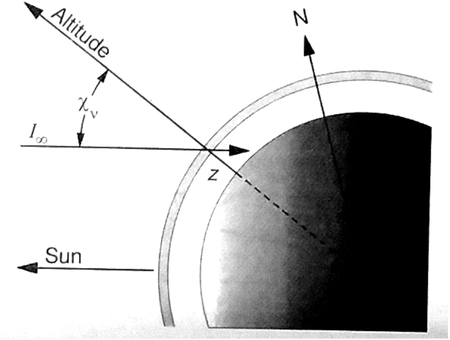
- Ionosphere is the transition region between fully ionized magnetospheric plasma and neutral atmosphere.
- It is a mixture of ionized and neutral particles: partially ionized plasma.
- Therefore, Coulomb and neutral collisions may contribute to electrical conductivity.

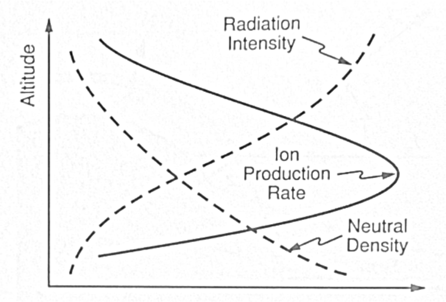



- Fully ionized plasmas: magnetosphere, solar wind; partially ionized plasma: Sun's photosphere, chromosphere, ionosphere
- There are two main sources of ionization: ultraviolet radiation from the Sun and precipitation of energetic particles from the magnetosphere into the atmosphere.

# Solar Ultraviolet (UV) Ionization

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

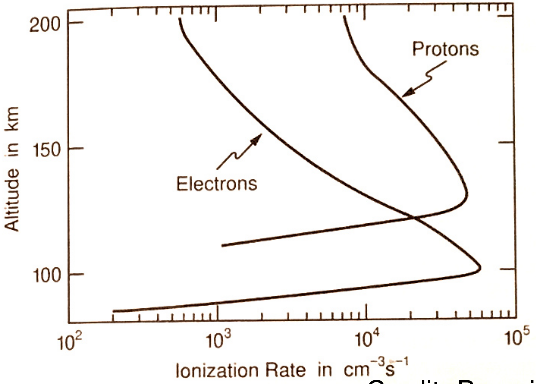



Credit: Baumjohann+Treumann

# 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

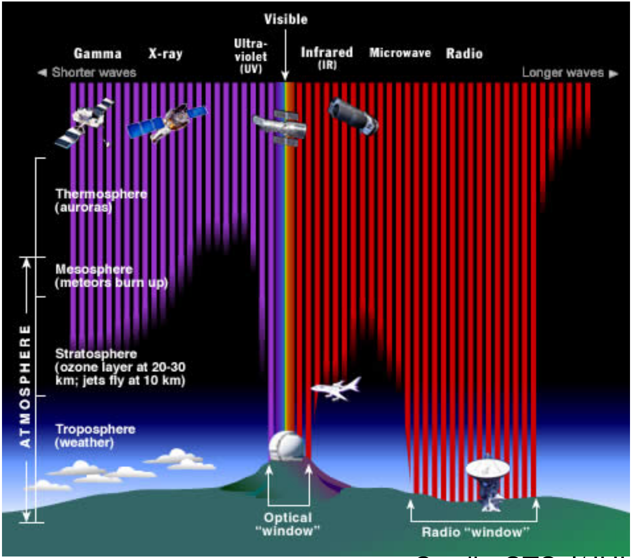



Credit: Baumjohann+Treumann

# Recombination and Attachment

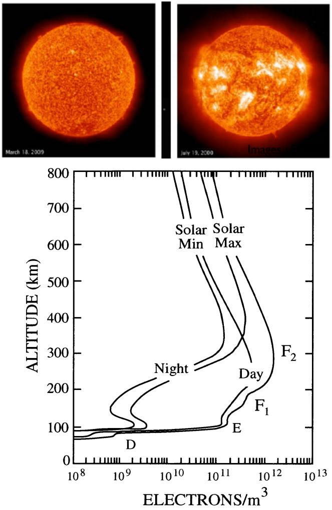
- The production of ionization in the ionosphere either by solar UV radiation or by energetic particles would, if it continued endlessly, lead to full ionization of the upper atmosphere.
- In reality two processes counteract the ionization:
    1. Recombination of ions and electrons to reform neutral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

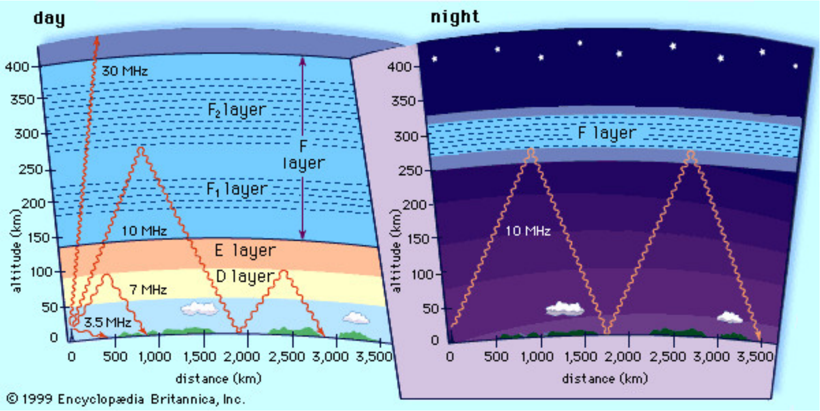



Credit: Paschmann+02

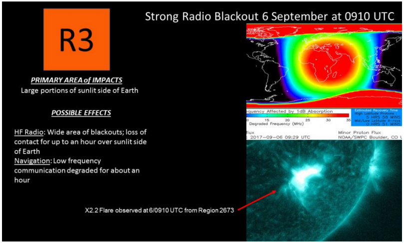
- D-layer is connected with the most energetic precipitation.
- E-layer contains mainly $O_2^+$ and $NO^+$ ions produced by UV radiation (100–150 nm) and solar X-rays (1–10 nm).
- F1-layer is composed of mainly $O^+$ produced by UV radiation in the range from about 17 to 91 nm.
- F2-layer is also composed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

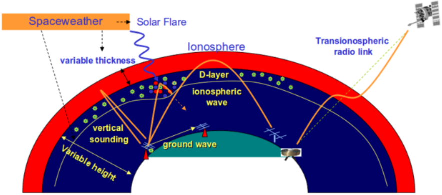
F-layer is the most important region for long distance HF radio communications.

# Ionospheric layers and HF radio communication



- 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.



## During a mild geomagnetic storm on Feb 4, 2022 40 from 49 Starlink satellites were burned in the atmosphere

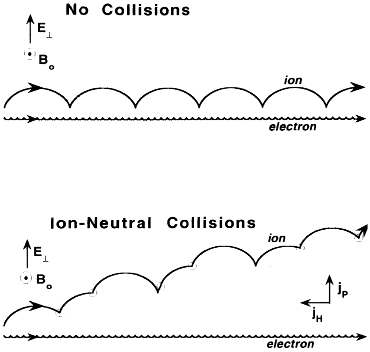
- Ionospheric dynamics was not well predicted.
- Atmospheric drag is caused by frequent collisions of molecules with a satellite. It reduces the altitude of satellite's orbit and leads to re-entry.

Source: ROOM

# 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:

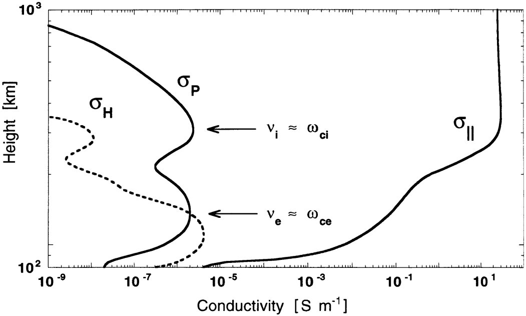
  1. the field-aligned (parallel) current $\mathbf{j}_{\parallel} = \sigma_{\parallel} \mathbf{E}_{\parallel}$
  2. the Pedersen current $\mathbf{j}_{\mathbf{P}} = \sigma_P \mathbf{E}_{\perp}$ flowing parallel to the transverse electric field $\mathbf{E}_{\perp}$
  3. the Hall current $\mathbf{j}_{\mathbf{H}}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




Credit: Menk&Waters + Paschmann+02

# Ionospheric conductivity

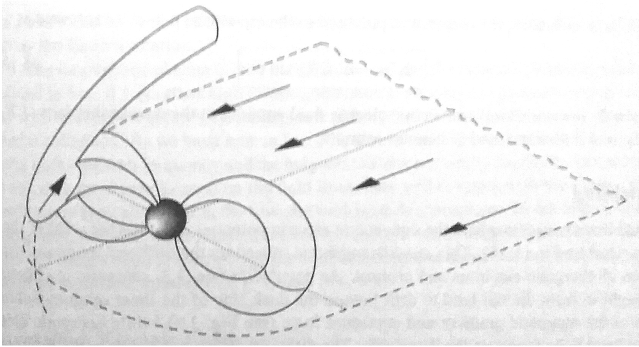
The conductivities are defined as $\sigma_{\parallel} = \sum_{s} \frac{n_s q_s^2}{m_s \nu_s}$, $\sigma_P = \sum_{s} \frac{n_s q_s^2}{m_s} \frac{\nu_s}{\nu_s^2 + \omega_{cs}^2}$ and $\sigma_H = -\sum_{s} \frac{n_s q_s^2}{m_s} \frac{\omega_{cs}}{\nu_s^2 + \omega_{cs}^2}$, where $n_s, q_s, m_s$ and $\nu_s$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




Credit: Paschmann+02

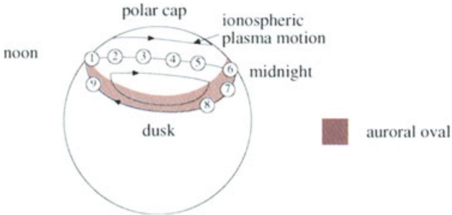
# Plasma Convection

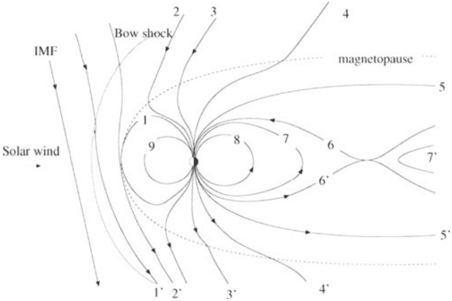
- Flux tube and plasma convection caused by magnetic merging



Credit: Baumjohann+Treumann

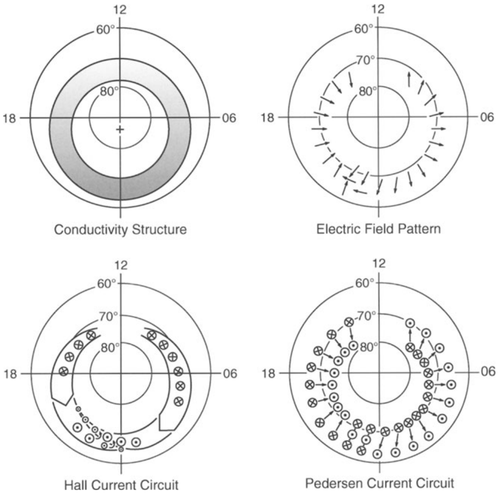
# Reflection of the convection in the ionosphere




Credit: Paschmann+02, Kivelson&Russell

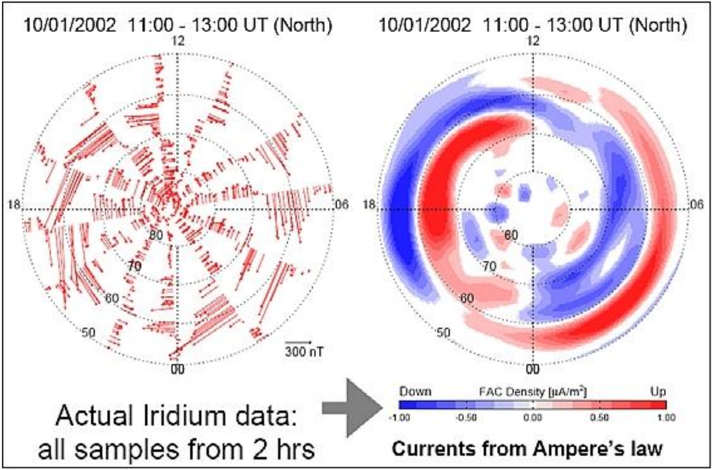
# Currents in the ionosphere




Credit: Baumjohann+Treumann

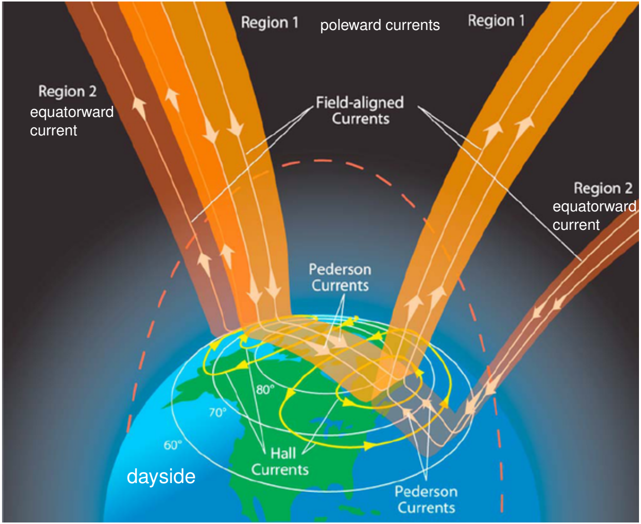
# Currents in the ionosphere

## AMPERE (Active Magnetosphere and Planetary Electrodynamics Response Experiment) observations




Credit: JHU/APL

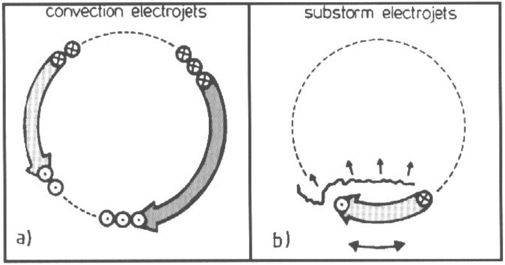
# Ionosphere-Magnetosphere coupling




Le+2010; also Wikipedia

# Currents during substorm

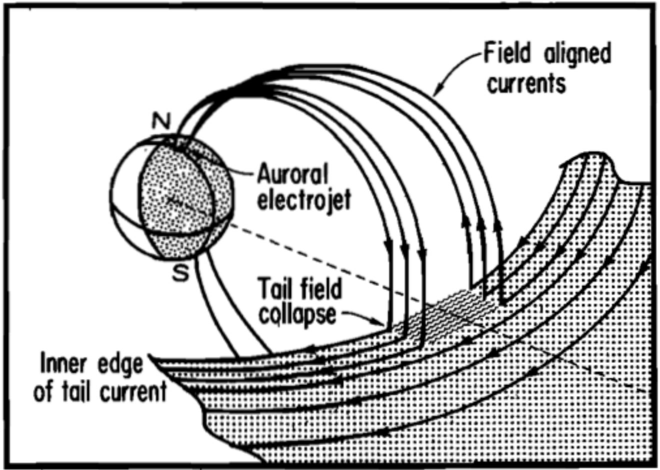
- Left side: convection electric field during substorm strengthens convection auroral electrojets (Hall currents, travel around the E region)
- Right side: substorm electrojet is formed by the substorm current wedge (Hall current)
- The strength of substorm electrojet is mainly determined by increase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




Credit: Cravens, 1997

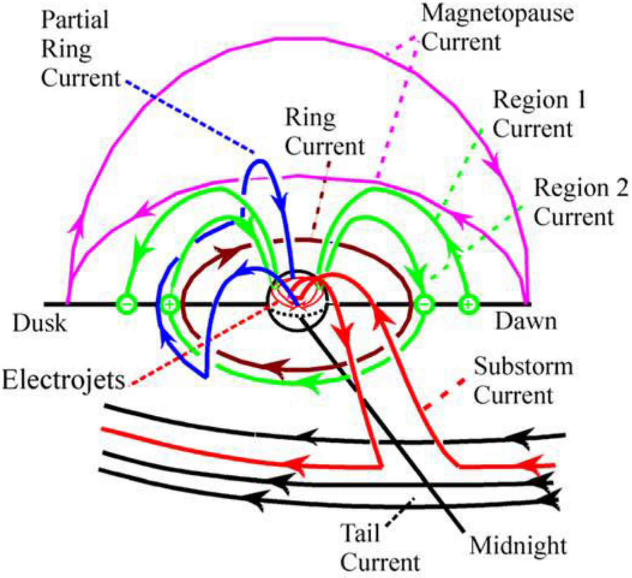
# Substorm Current Wedge

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

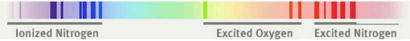


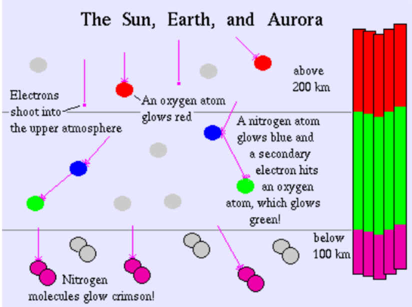

McPherron&Chu 16

# Ionosphere-Magnetosphere coupling

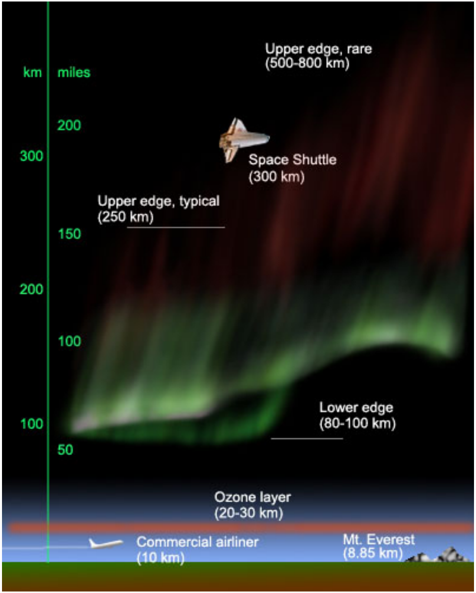


# Aurora: colors




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



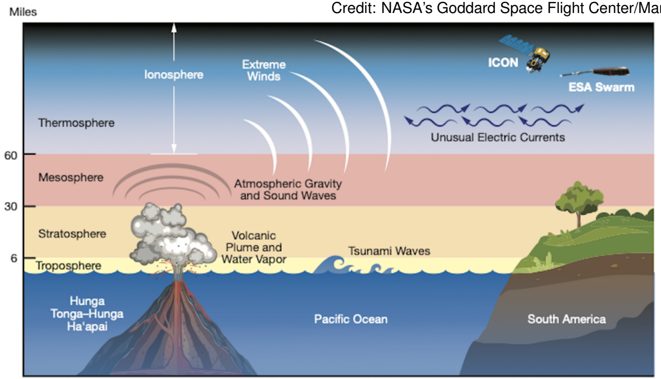
# Aurora: forms



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

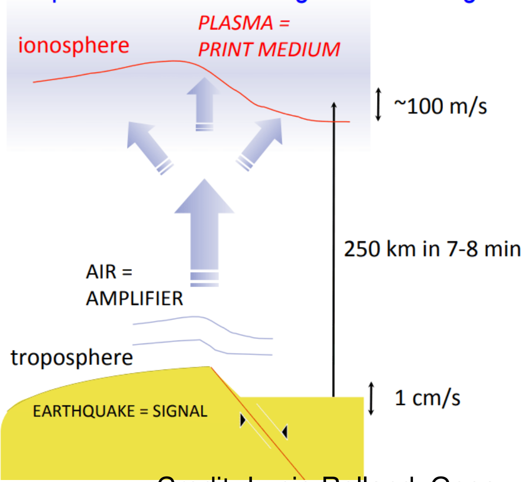
- The explosion created large pressure disturbances in the atmosphere, leading to strong winds which affected electric currents.
- The equatorial electrojet surged to five times its normal peak power and dramatically flipped direction, flowing westward for a short period (as due to the ring current).
- 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

Ionosphere is sensitive to ground shaking

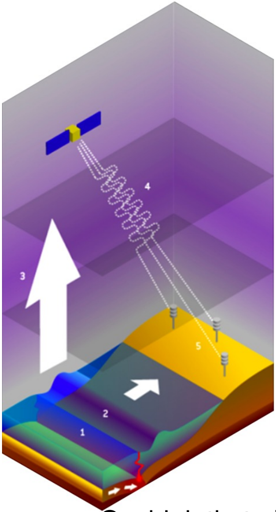


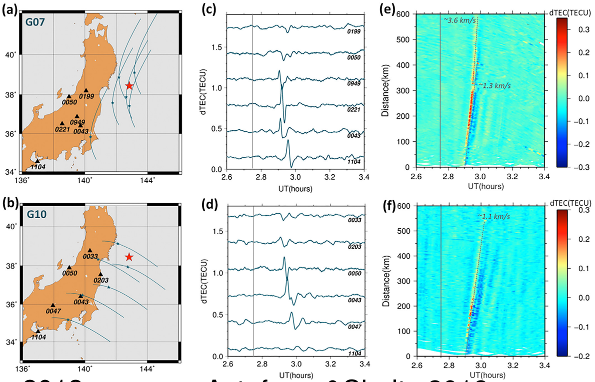

Credit: Lucie Rolland, Geoazur/OCA/UCA

# 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.

Mw7.4 Sanriku-oki earthquake of 9 March 2011

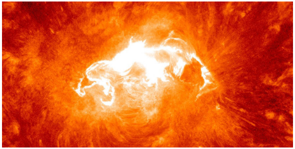


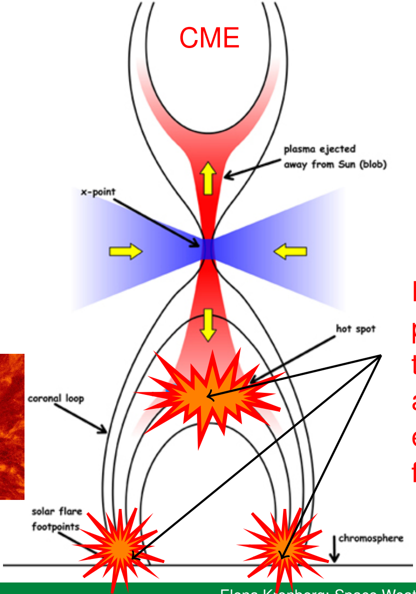




Occhipinti et al., 2013

Astafyeva&Shults 2018

# Chromosphere and Ionosphere: anology






Partcile precipitation triggers ionization and release of energy $\rightarrow$ 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