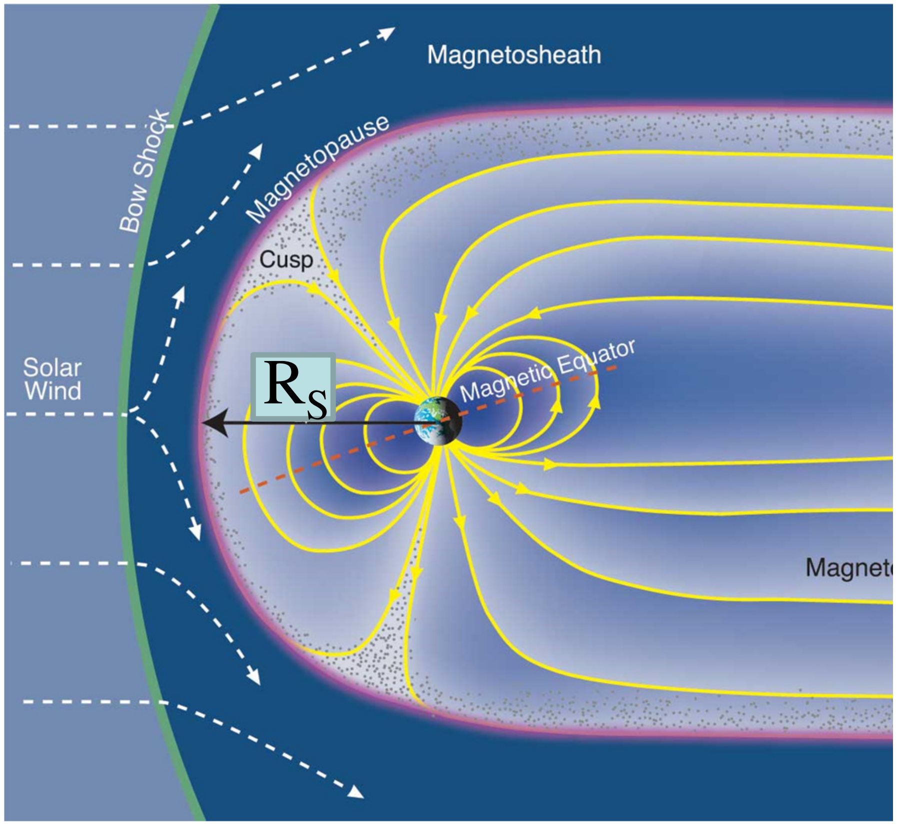
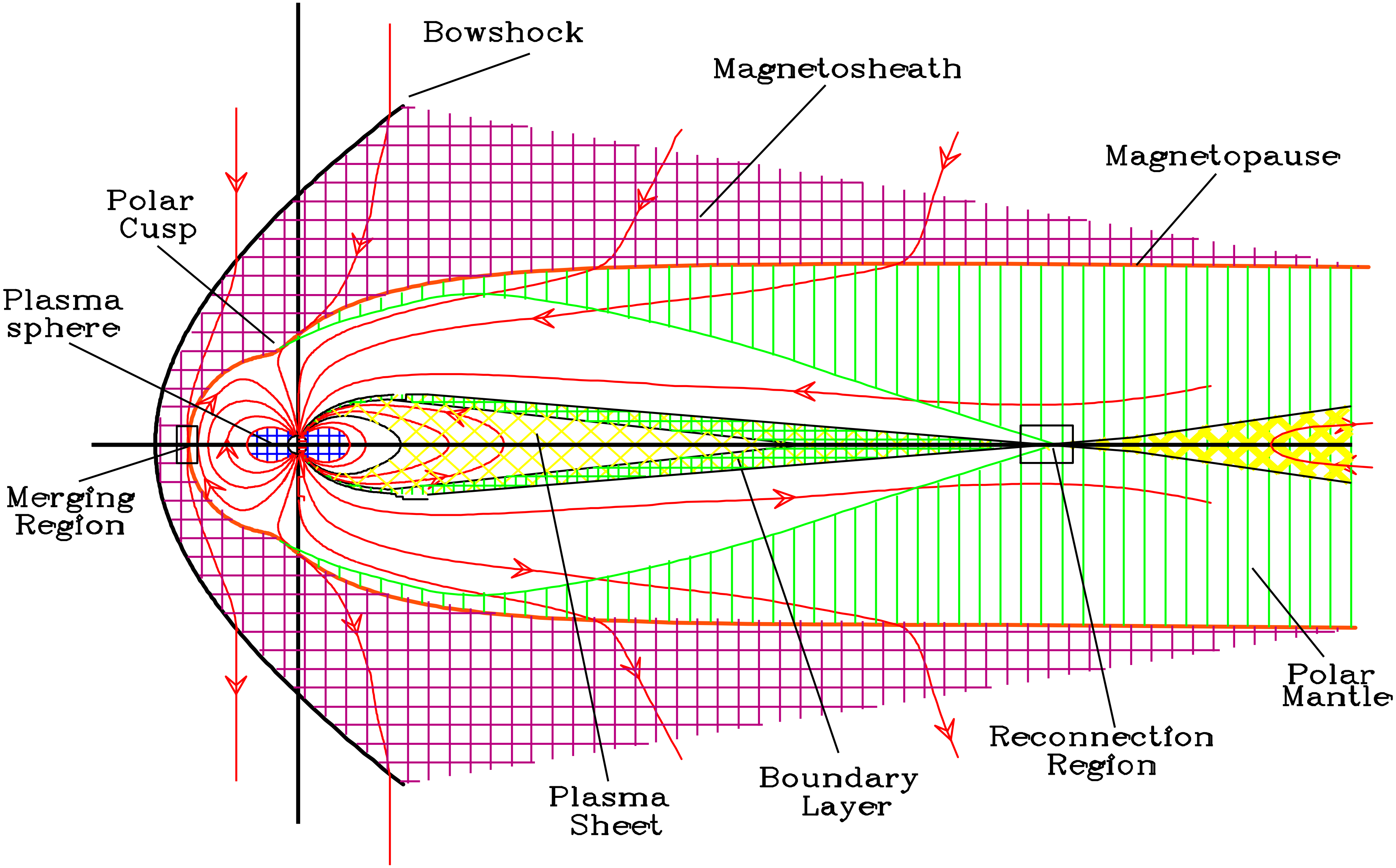
24. Radiation belts.
Ionosphere.

Forming the Magnetopause

- The solar wind is supersonic and passes through a **bow shock** where the direction of flow is changed so that most of the solar wind plasma is deflected to either side of the magnetopause.
- The zone of shocked solar wind plasma is the **magnetosheath.**
- The dynamic pressure is much larger than the thermal pressure or magnetic pressure in the solar wind.
- Within the magnetosphere the magnetic pressure of the Earth's internal field dominates.
- To a good approximation the boundary (the magnetopause) between the region dominated by the solar wind and the region dominated by the Earth (the magnetosphere) can be found by balancing the solar wind dynamic pressure with the magnetic pressure of the Earth.



The Magnetotail - Noon Midnight View



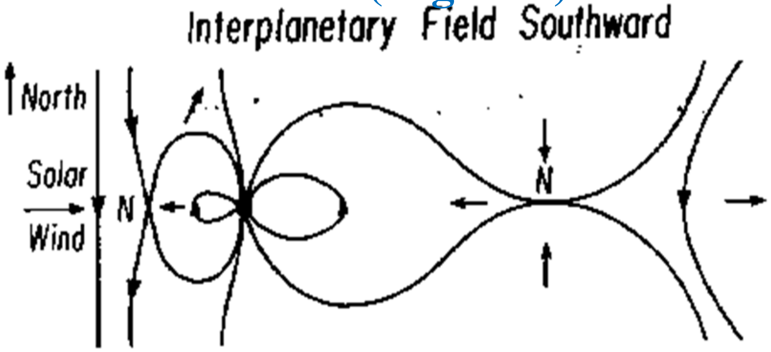
Interaction between the IMF and magnetosphere.

The IMF is a vector quantity with three directional components, two of which (B_x and B_y) are oriented parallel to the ecliptic. The third component, B_z , is perpendicular to the ecliptic and is created by waves and other disturbances in the solar wind.

When the IMF and geomagnetic field lines are oriented opposite or "antiparallel" to each other, they can "merge" or "reconnect," resulting in the transfer of energy, mass, and momentum from the solar wind flow to magnetosphere.

The strongest coupling –with the most dramatic magnetospheric effects– occurs when the B_z component is oriented southward.

Bz southward (negative)



Bz northward (positive)

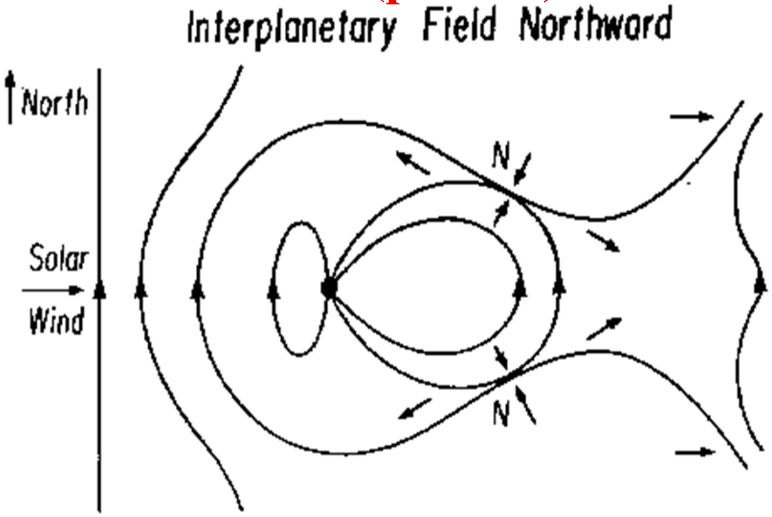
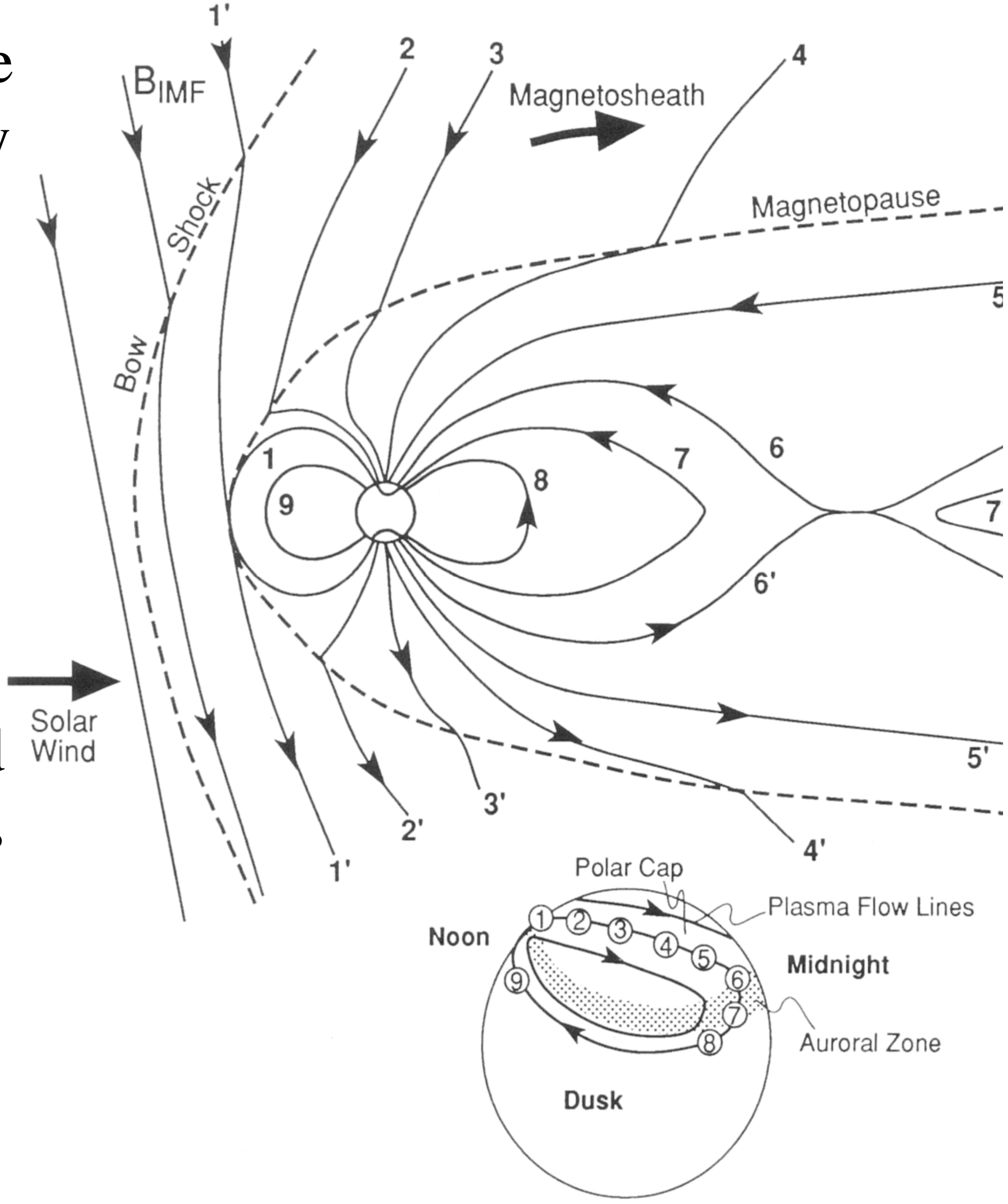


Figure 2

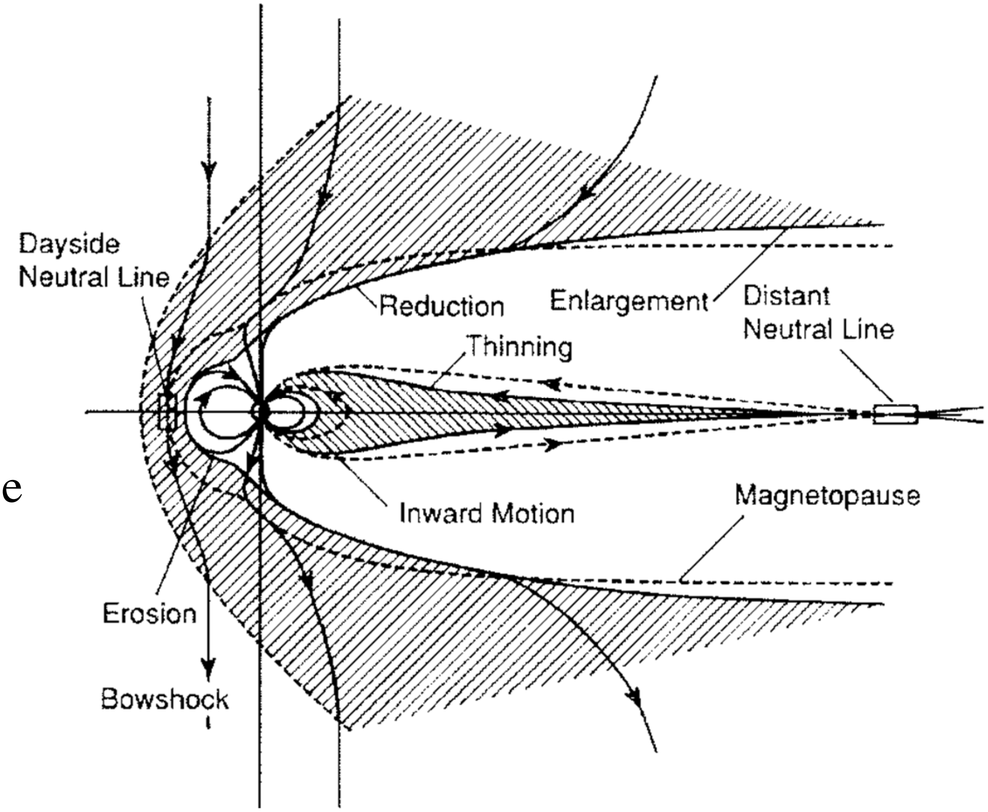
Magnetospheric Convection

- •The newly reconnected flux tube will move be dragged tailward by the solar wind.
- • At a tail reconnection site the lobe field lines reconnect at position to form new closed field lines.
- •The new closed field lines are stressed and moves earthward.
- •The flow circuit is finally closed when the newly closed field lines flow magnetosphere dayside.



The Events in the Magnetosphere During a Substorm – Growth Phase

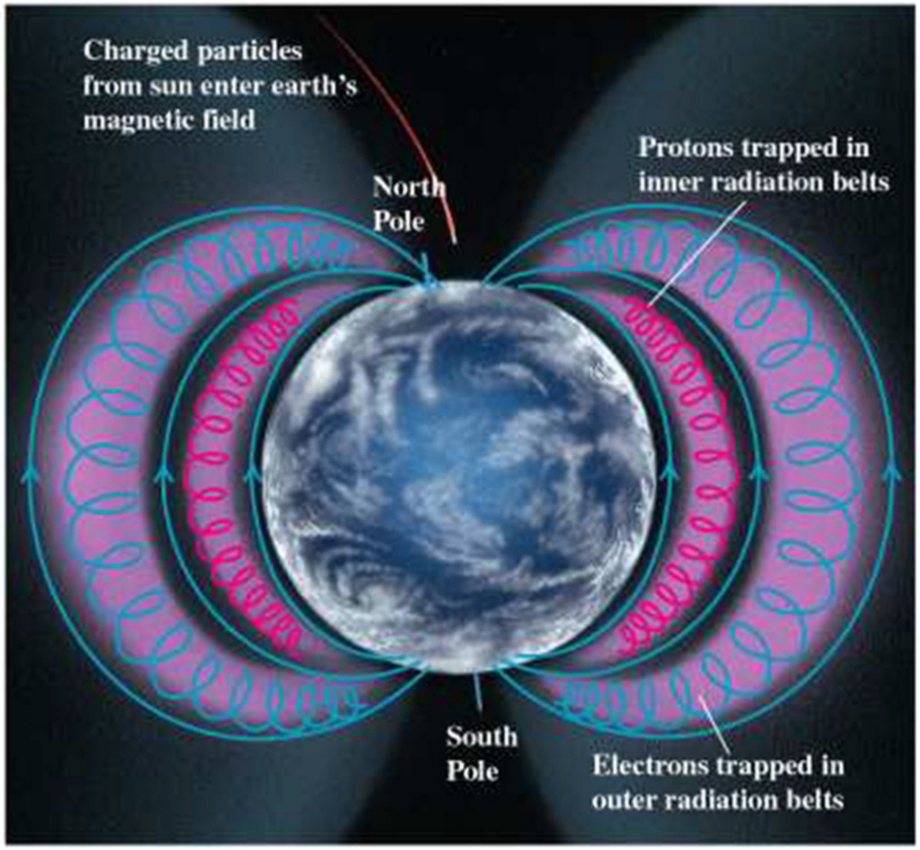
- A southward turning of the IMF initiates or increases dayside reconnection.
  - Magnetic flux from the Earth connects to the IMF and is transported over the polar caps into the lobes.
  - The return flow in the magnetosphere is unable to return flux to the dayside as fast as it is removed. The dayside magnetopause is eroded.
- The magnetic field in the tail lobes increases storing energy for later release.
- The plasma sheet thins.



Van Allen Radiation Belts

The Earth has two regions of trapped fast particles. The inner radiation belt discovered by Van Allen is relatively compact, extending perhaps one Earth radius. It consists of very energetic protons, a by-product of collisions by cosmic ray ions with atoms of the atmosphere.

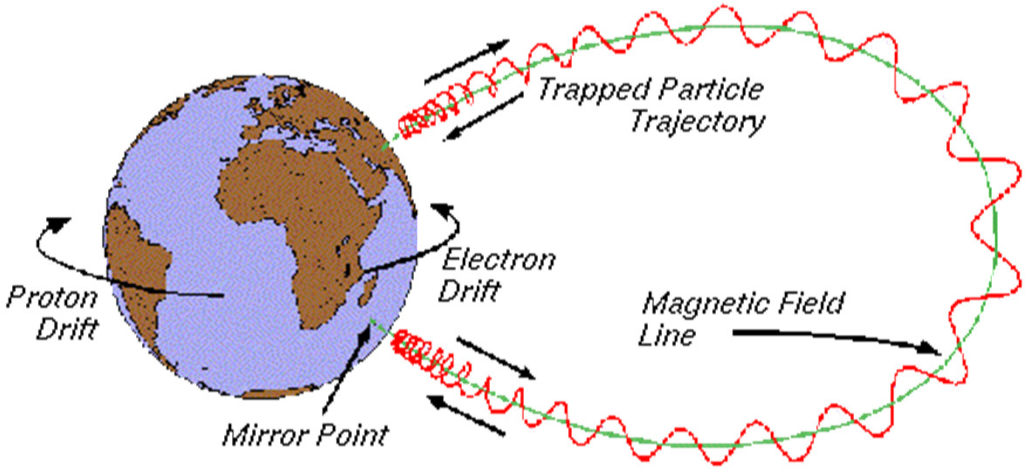
Further out is the large region of the ring current, containing ions and electrons of much lower energy (the most energetic among them also known as the "outer radiation belt"). Unlike the inner belt, this population fluctuates widely, rising when magnetic storms inject fresh particles from the tail of the magnetosphere, then gradually falling off again. The ring current energy is mainly carried by the ions, most of which are protons.



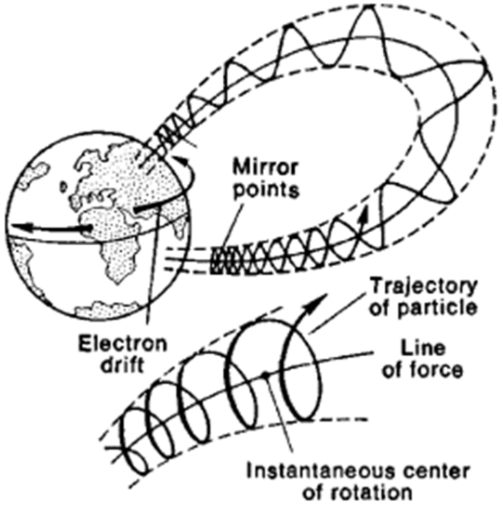
(a)

Motion of charged particles in the radiation belts

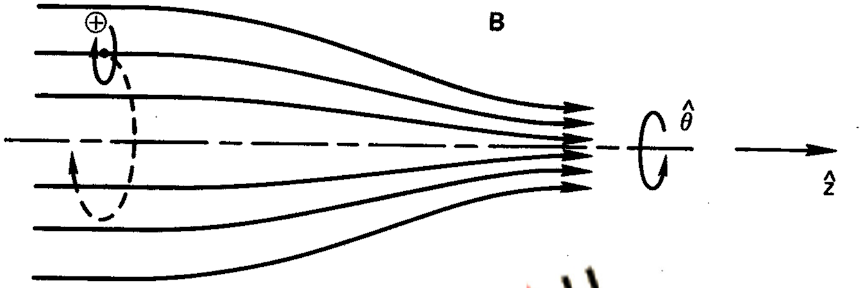
- **Electron motion in a steady-state dipole-like magnetic field can be exactly described by three periodic motions**
  - gyration around the magnetic field
  - bounce along the magnetic field mirror points
  - azimuthal gradient-curvature drift around the magnetosphere.



- **Each has an associated Hamiltonian invariant which is approximately conserved under adiabatic changes to the magnetic field.**
- **Because the magnetic field increases closer to the Earth the Larmor radius decreases and the rotational velocity increases. When the rotational velocity reaches the value of the total velocity the particles cannot move further down and are reflected.**



Magnetic moment of particle in magnetic field



- Consider motion of a particle with charge e in an axisymmetric magnetic field.
- Calculate the magnetic moment of a particle moving on a circular orbit :

$\mu = \frac{1}{c} I \cdot A,$ where A is the orbit area, I is the electric current

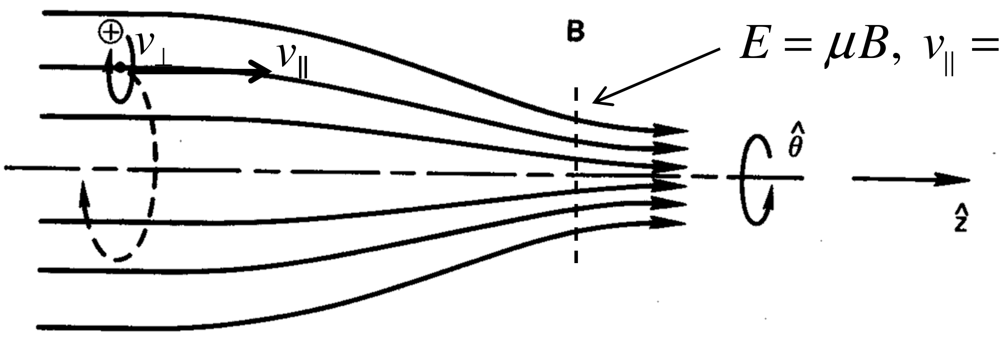
The effective current is $I = dQ/dt = e/P$, where P is the period of rotation;

$$P = \frac{2\pi}{\omega_c},\ A = \pi r_L^2,\ \omega_c = \frac{eB}{mc}.$$

Here, r_L is the Larmor radius, ω_c is the cyclotron frequence.

Then, $\mu = \frac{e}{c}\frac{\omega_c}{2\pi}\pi r_L^2 = \frac{1}{2}\frac{mv_\perp^2}{B}$. The magnetic moment is conserved.

Magnetic mirror



$E = \mu B,\ v_\parallel = 0$ - mirror reflection point

If $E > \mu \max(B)$ then particle escapes – "loss cone" condition

The important property of the magnetic moment is that it remains invariant. When the particle moves in regions of stronger field the Larmor radius changes but μ remains constant. The particle kinetic energy E is conserved:

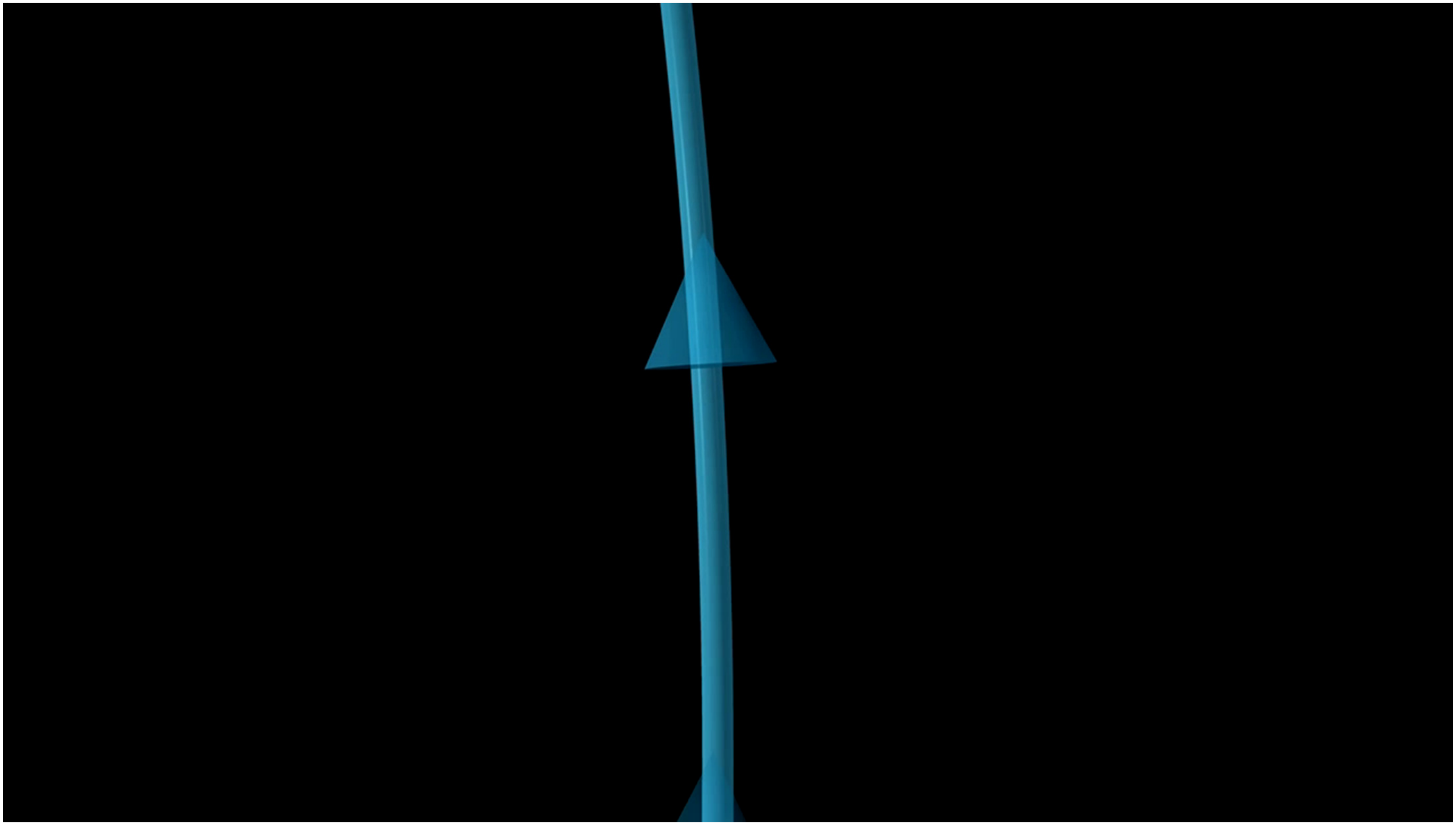
$$mv_\parallel^2/2 + mv_\perp^2/2 = E.$$

Using the definition of the magnetic moment: $\mu = mv_\perp^2/2B$ we get:

$$mv_\parallel^2/2 + \mu B = E.$$

If B increases as particle moves then $v_\perp$ increases, hence $v_\parallel$ decreases, and may become zero because: $mv_\parallel^2/2 = E - \mu B$.
At this point, where $E = \mu B$, the particle stops and reverses the direction of motion. This is the effect of *magnetic mirror*.

Animation of particle motion in the radiation belts



Thanks to G. Stevens, S. Ukhorskiy, and APL team for movie

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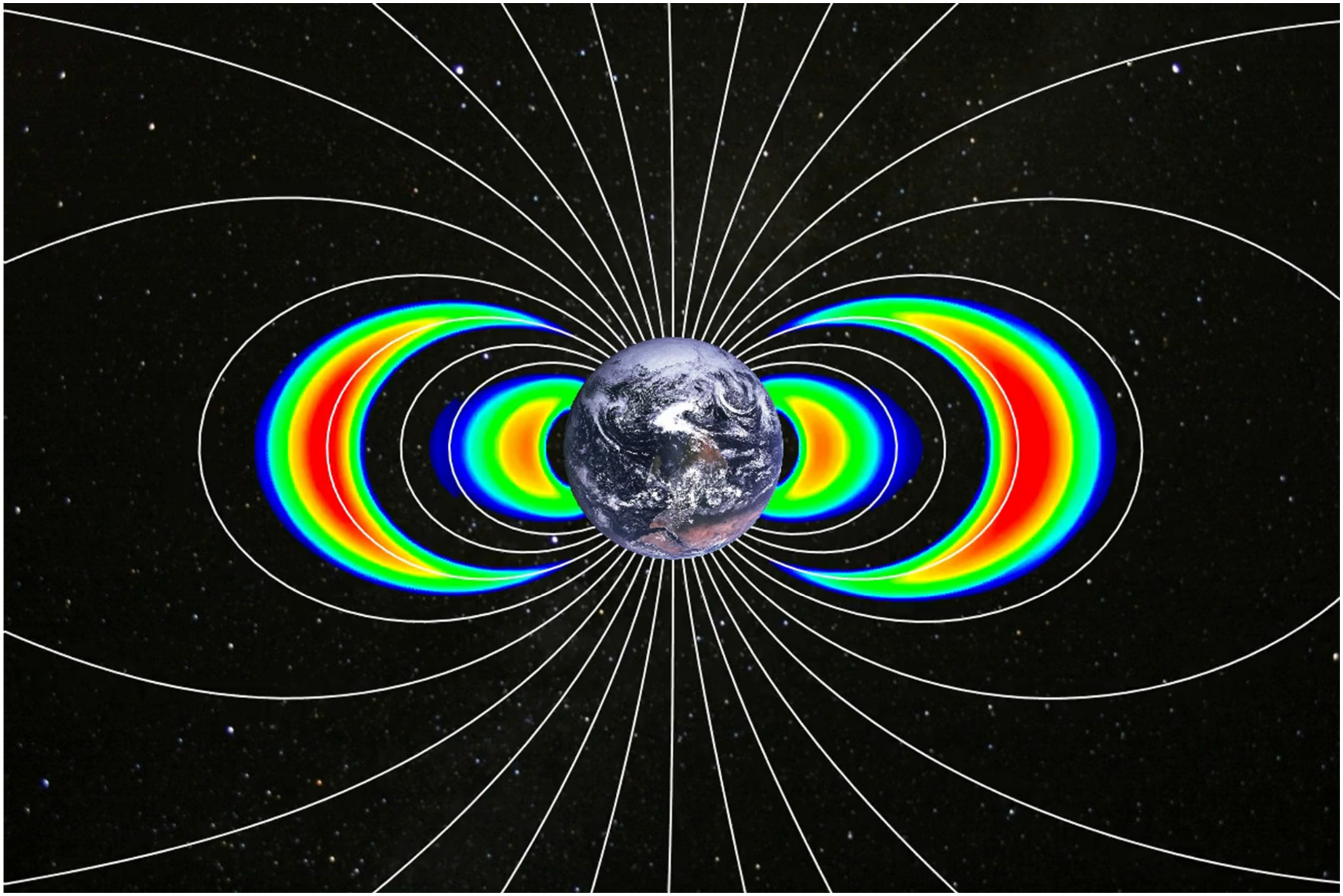
Dynamic Belts (Baker et al., 2013)



Courtesy G. Stevens, and S. Ukhorisky

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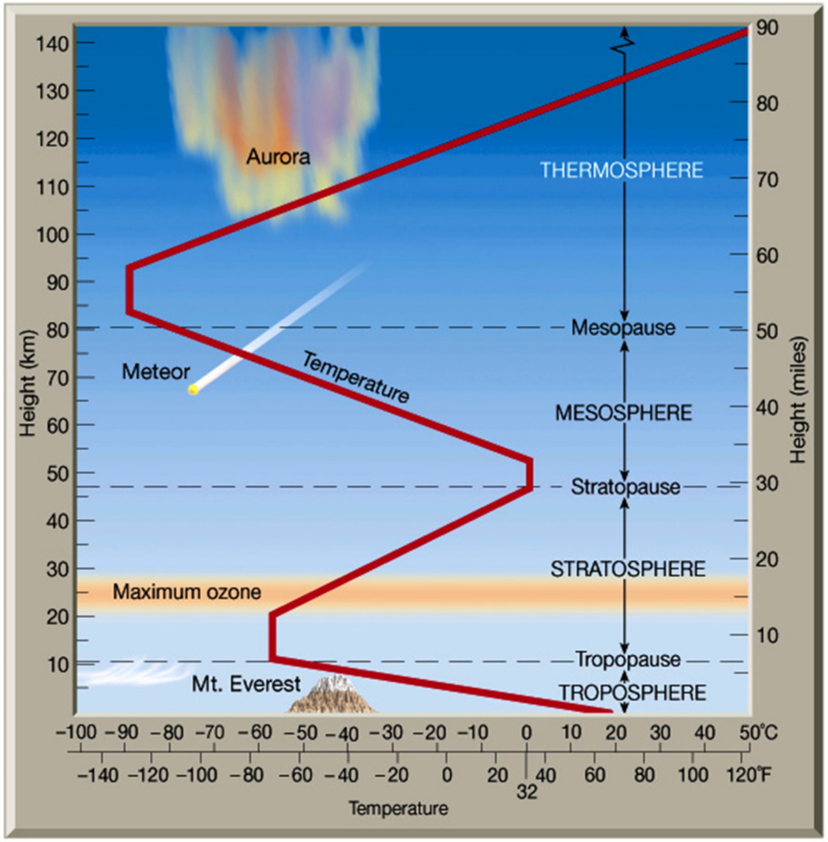
Discovery of new radiation belt by Van Allen Probes (2013)

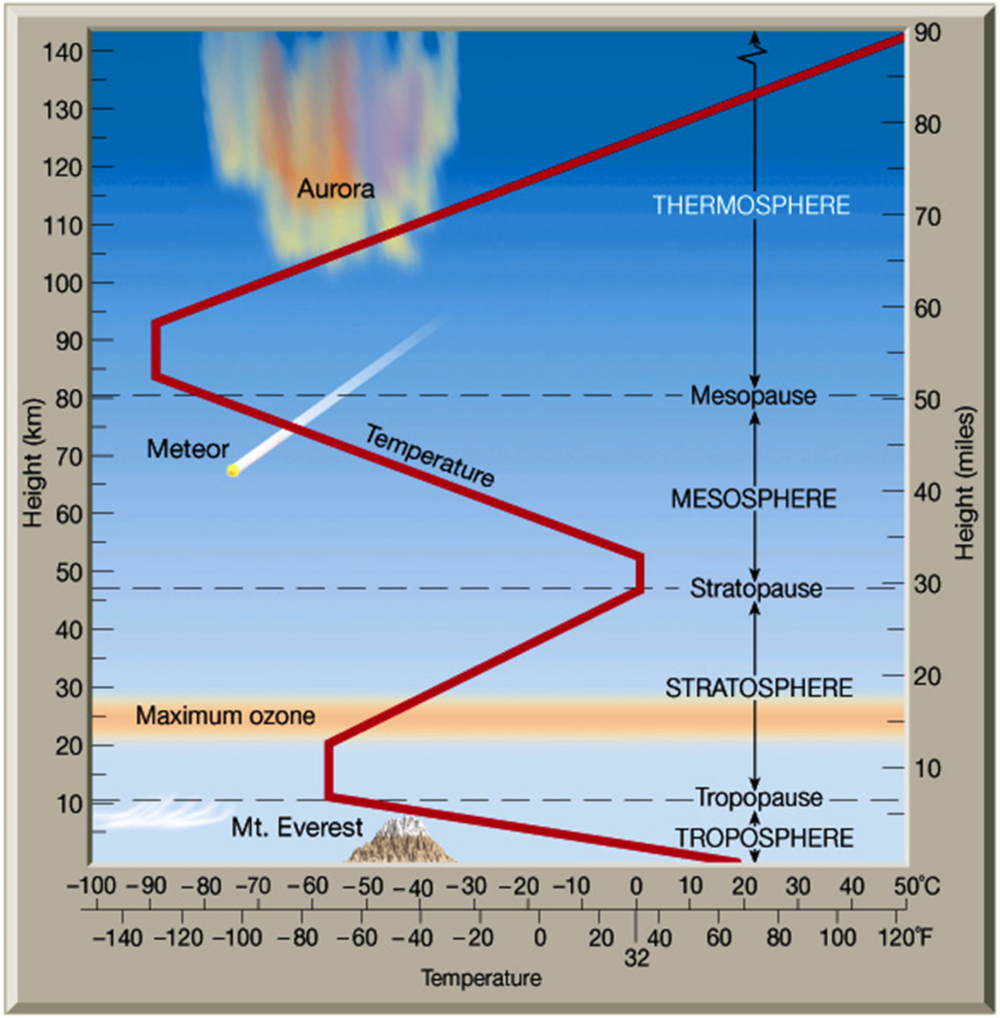
The Earth's Atmosphere

- The Earth's upper atmosphere is important for ground-based and satellite radio communication and navigation.
- Its density determines the lifetime of satellites in low-Earth orbit.
- It is important for auroras and magnetospheric convection.
- The upper atmosphere is called the thermosphere. It is composed mostly of neutral atoms and molecules.
- Within the thermosphere the amount of ionized gas becomes important and forms a region called the ionosphere.
- These two co-located regions are coupled through particle collisions (neutral – ion).

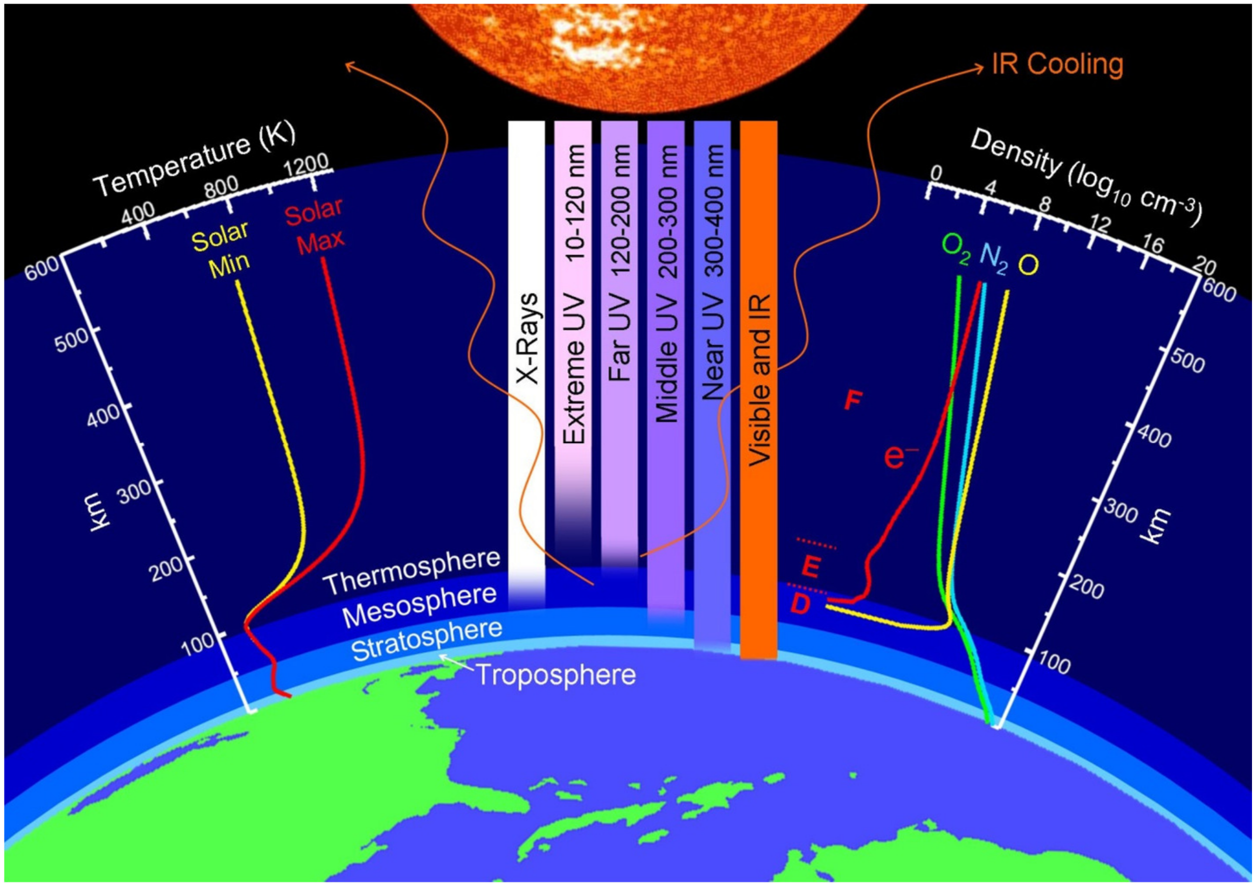


The Structure of the Atmosphere

- Troposphere (water vapor, convection due to contact with surface, expansion of air)
- Stratosphere (ozone layer)
- Mesosphere (radiative cooling)
- Thermosphere (X-ray, particle energy input heats this layer)
- Ionosphere (region with appreciable ionized component - balance of production and loss)



Layers of Earth's upper atmosphere.

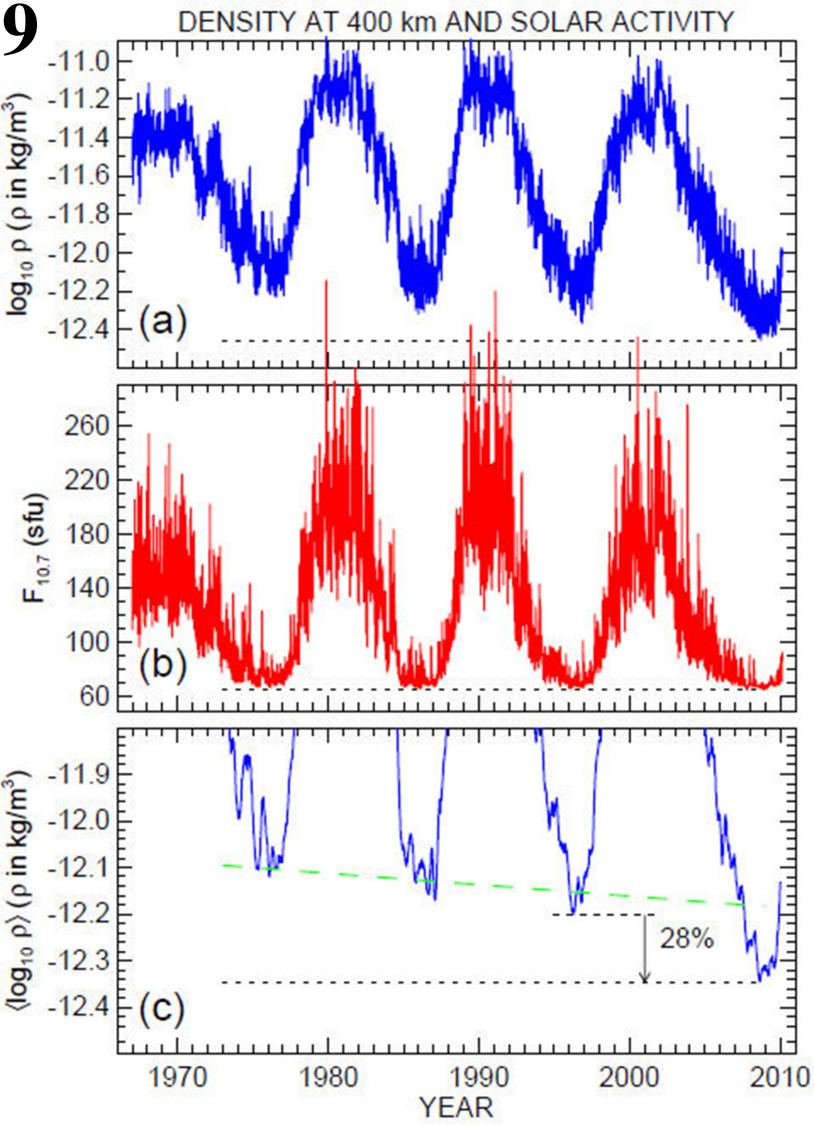


Credit: John Emmert/NRL.

The thermosphere ranges in altitude from 90 km to 600+ km. The thermosphere intercepts extreme ultraviolet (EUV) photons from the Sun before they can reach the ground. When solar activity is high, solar EUV warms the thermosphere, causing it to expand. (This heating can raise temperatures as high as 1400 K—hence the name thermosphere.) When solar activity is low, the opposite happens.

A Puzzling Collapse of Earth's Upper Atmosphere in 2008-2009

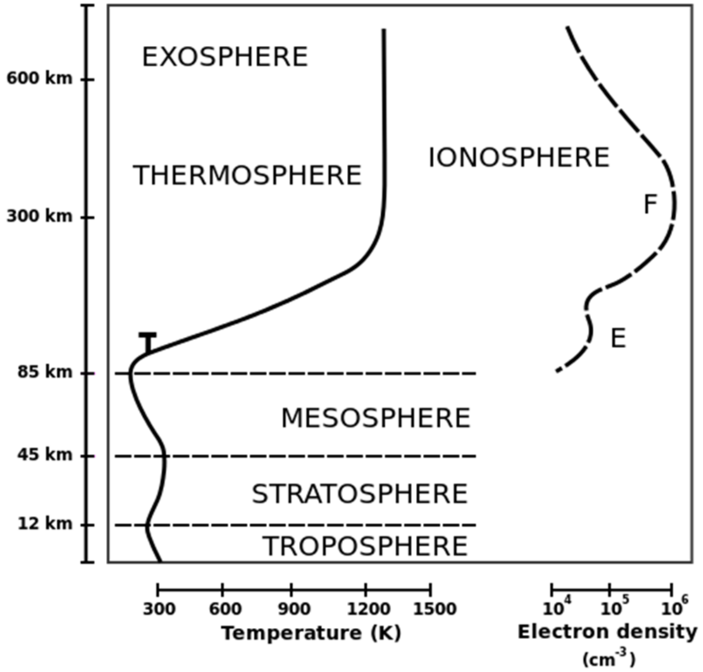
- In 2008 -2009, the Sun plunged into a century-class solar minimum. Sunspots were scarce, solar flares almost non-existent, and solar EUV radiation was very low.
- John Emmert used a clever technique: Because satellites feel aerodynamic drag when they move through the thermosphere, it is possible to monitor conditions there by watching satellites orbital decay. He analyzed the decay of more than 5000 satellites ranging in altitude between 200 and 600 km during1967-2010.
- The thermospheric collapse was bigger than the Sun alone could explain.
- One possible explanation is carbon dioxide (CO_2). When carbon dioxide gets into the thermosphere, it acts as a coolant, shedding heat via infrared radiation. It is widely-known that CO_2 levels have been increasing in Earth's atmosphere. Extra CO_2 in the thermosphere could have magnified the cooling action of solar minimum.

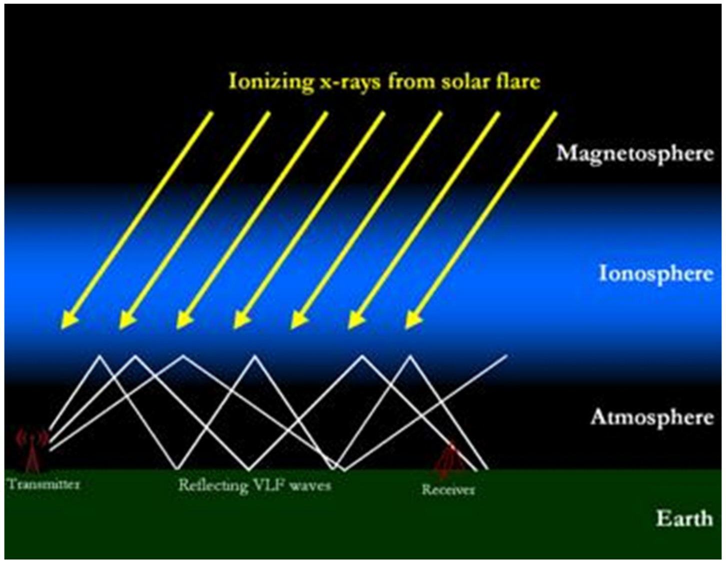


The density of the thermosphere (at a height of 400 km) during the past four solar cycles. Frames (a) and (c) are density; frame (b) is the Sun's radio intensity at a wavelength of 10.7 cm, a key indicator of solar activity. In 2008 and 2009, the density of the thermosphere was 28% lower than expectations set by previous solar minima. Emmert et al. (2010), Geophys. Res. Lett., 37, L12102.

The Ionosphere

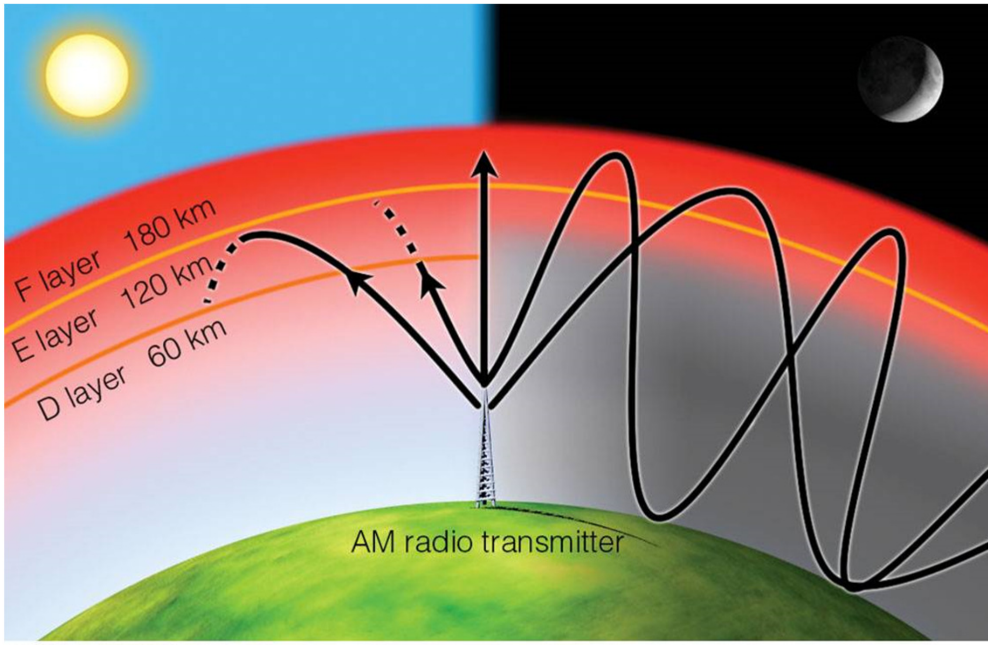
- Ions exist everywhere in the atmosphere but they are most important in the thermosphere.
- We call that ionized part of the thermosphere the ionosphere.
- The ions come from neutral atoms or molecules that have been ionized either by high energy photons (UV or X-rays- short wave lengths) from the Sun or energetic particles from the magnetosphere that precipitate into the atmosphere and collide with the surrounding gas.
- The number of ions in the thermosphere peaks at about 300 km height – the region about this peak is the ionosphere.





The Discovery of the Ionosphere

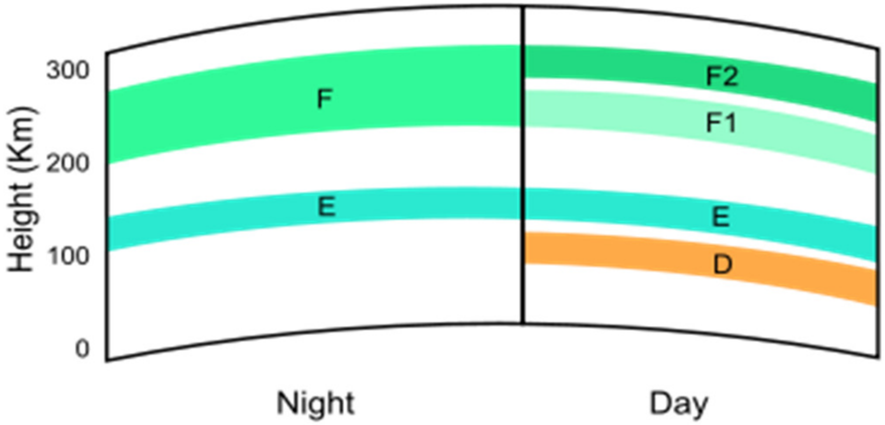
- Guglielmo Marconi's demonstration of long distance radio communication in 1901 started studies of the ionosphere.
- Arthur Kennelly and Oliver Heaviside independently in 1902 postulated an ionized atmosphere to account for radio transmissions. (Kennelly-Heavyside layer is now called the E-layer).
- Larmor (1924) developed a theory of reflection of radio waves from an ionized region.
- Breit and Tuve in 1926 developed a method for probing the ionosphere by measuring the round-trip for reflected radio waves.



- The ionosphere is important for radio wave (AM only) propagation.
- Ionosphere is composed of the D, E, and F layers.
- The D layer is good at absorbing AM radio waves. D layer disappears at night. The E and F layers bounce the waves back to the Earth.
- This explains why radio stations adjust their power output at sunset and sunrise.

The Ionosphere During the Day and at Night

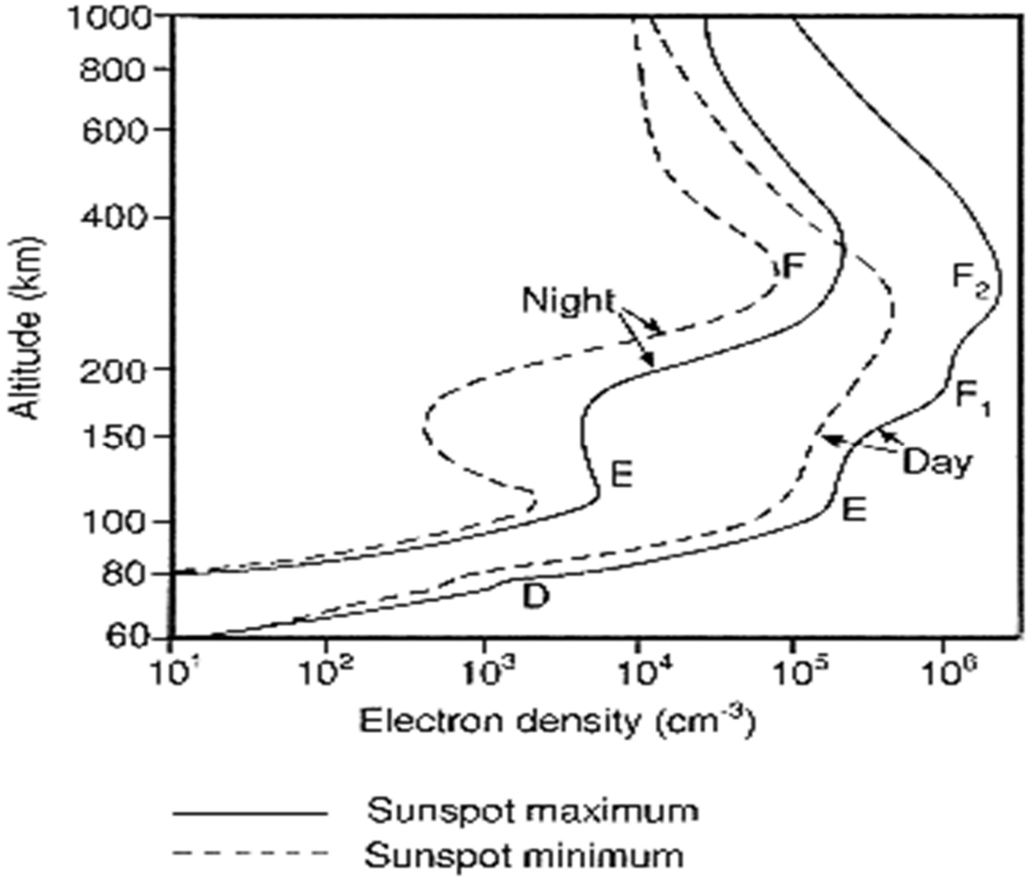
- The main ionization mechanism is photoionization therefore the highest densities in the ionosphere are on the sunlit side of the Earth.
- The ionosphere does not go away at night – the recombination time (time for an electron and ion to come back together) is comparable to the rotation period of the Earth.
- In the auroral zone precipitating particle (particles whose mirror altitude is in the atmosphere) also ionize particles.



- *The D layer is the innermost layer*, 60 - 90 km above the surface. Ionization here is due to Lyman-alpha hydrogen radiation at a wavelength of 121.5 nm ionizing nitric oxide (NO). In addition, high solar activity can generate hard X-rays (wavelength < 1 nm) that ionize N_2 and O_2.
- *The E layer is the middle layer*, 90 -150 km above the surface. Ionization is due to soft X-ray (1–10 nm) and far ultraviolet (UV) solar radiation ionization of molecular oxygen (O_2).
- *The F layer is the top layer,* 150 km to >500 km. EUV (10–100 nm) solar radiation ionizes atomic oxygen. Radio waves are mostly reflected from the F layer.

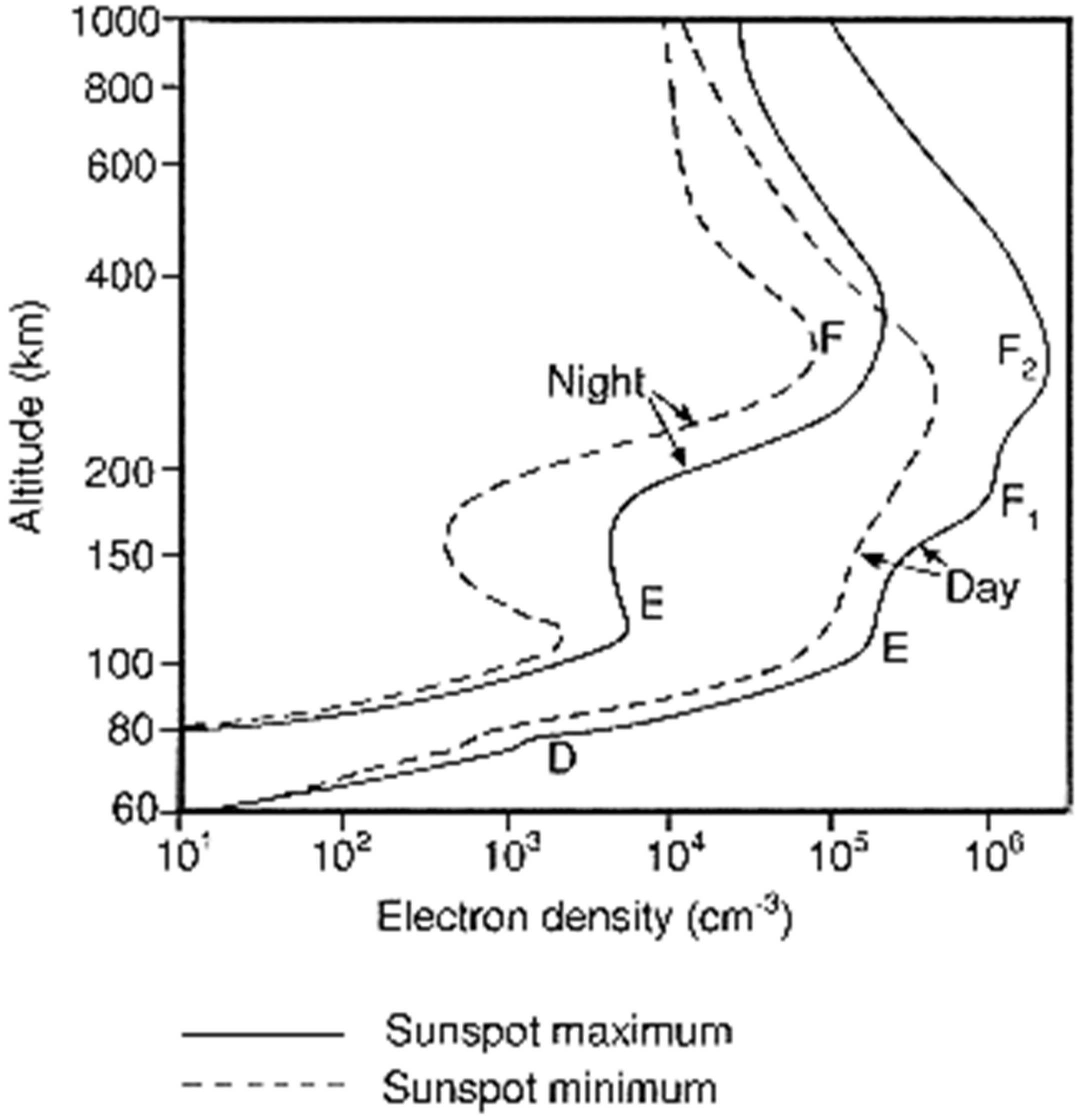
The Extent of the Ionosphere

- There are ions and electrons at all altitudes in the atmosphere.
- Below about 60km the charged particles do not play an important part in determining the chemical or physical properties of the atmosphere.
- Identification of ionospheric layers is related to inflection points in the vertical density profile.



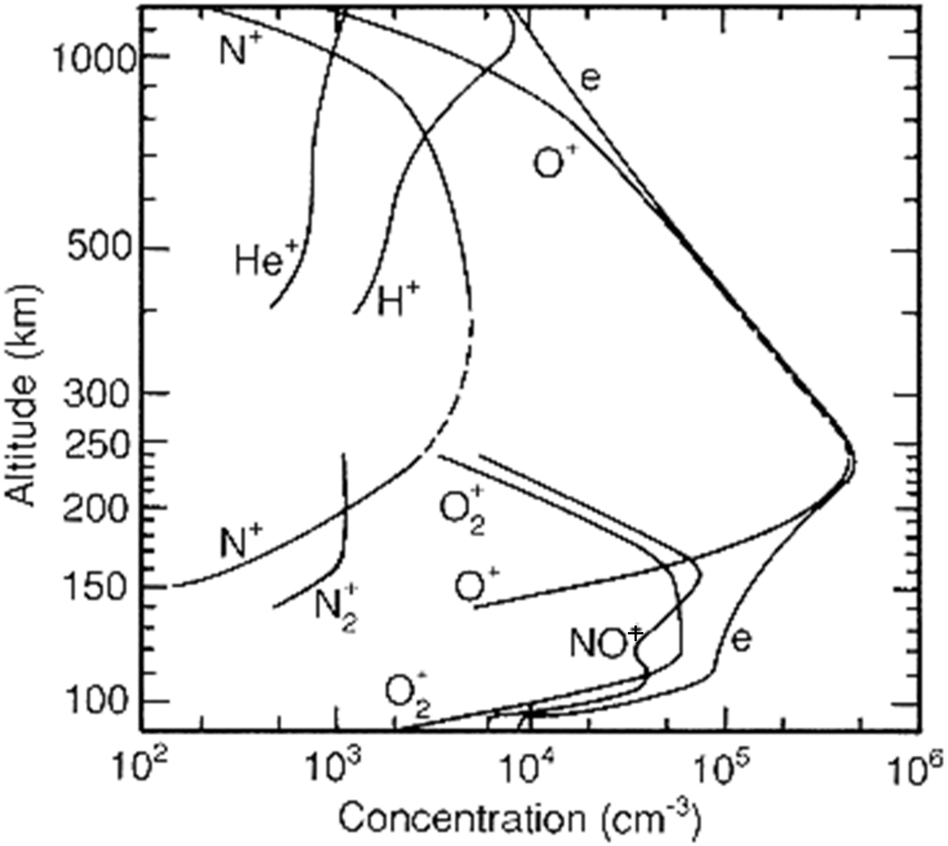
Diurnal and Solar Cycle Variations

- In general densities are larger during solar maximum than during solar minimum.
- The D and F_1 regions disappear at night.
- The E and F_2 regions become much weaker.
- The topside ionosphere is basically an extension of the magnetosphere.



Composition of the Dayside Ionosphere Under Solar Minimum Conditions

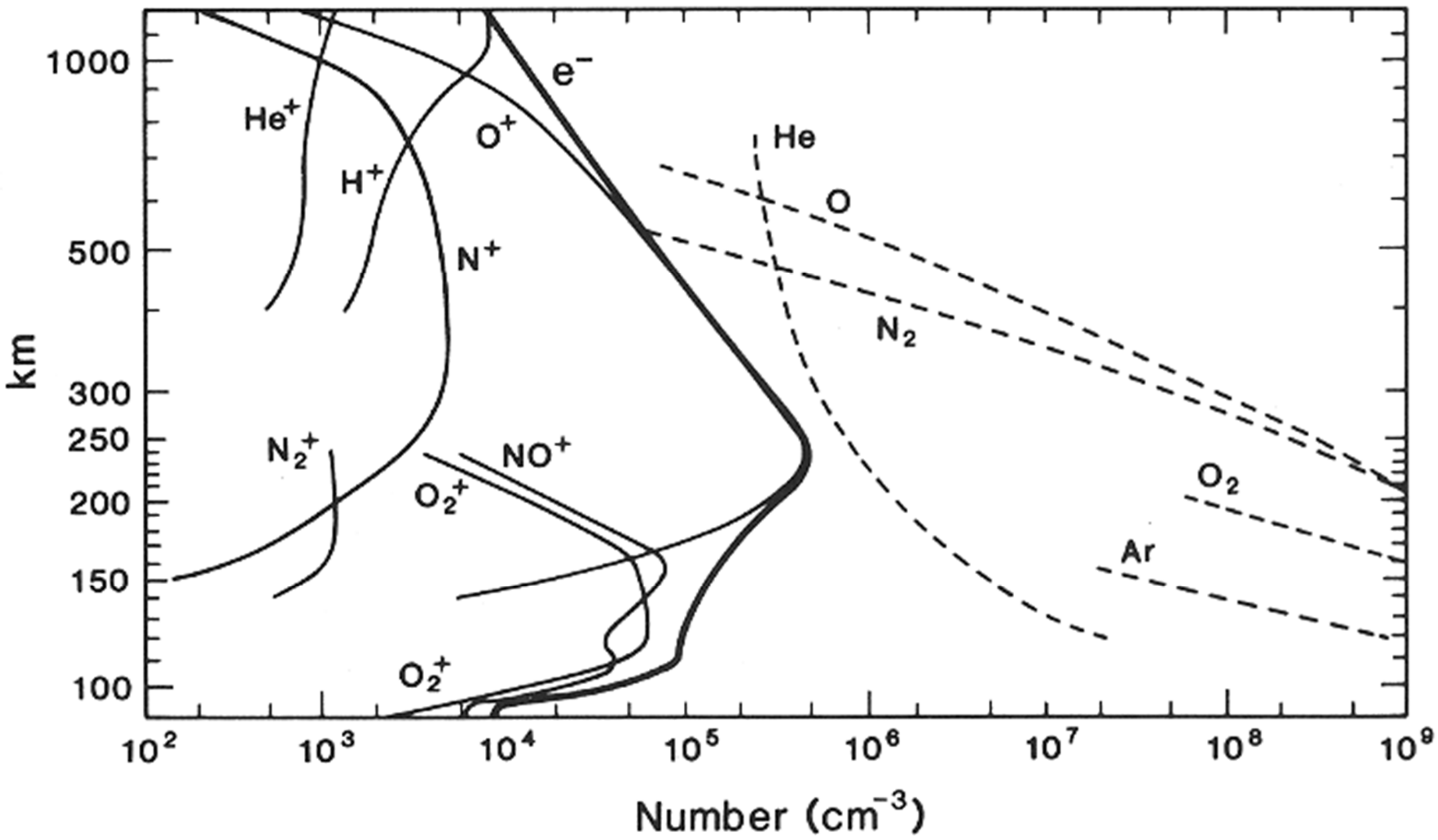
- At low altitudes the major ions are O_2^+ and NO^+
- Near the F_2 peak it changes t O^+
- The topside ionosphere is H dominant.



How is the Ionosphere Created?

- For practical purposes the ionosphere can be thought of as quasi-neutral (the net charge is practically zero in each volume element with enough particles).
- The ionosphere is formed by ionization of the three main atmospheric constituents N_2, O_2, and O.
  - The primary ionization mechanism is photoionization by extreme ultraviolet (EUV) and X-ray radiation.
  - In some areas ionization by particle precipitation is also important.
  - The ionization process is followed by a series of chemical reactions which produce other ions.
  - Recombination removes free charges and transforms the ions to neutral particles.

Neutral Density Exceeds the Ion Density Below About 500 km.



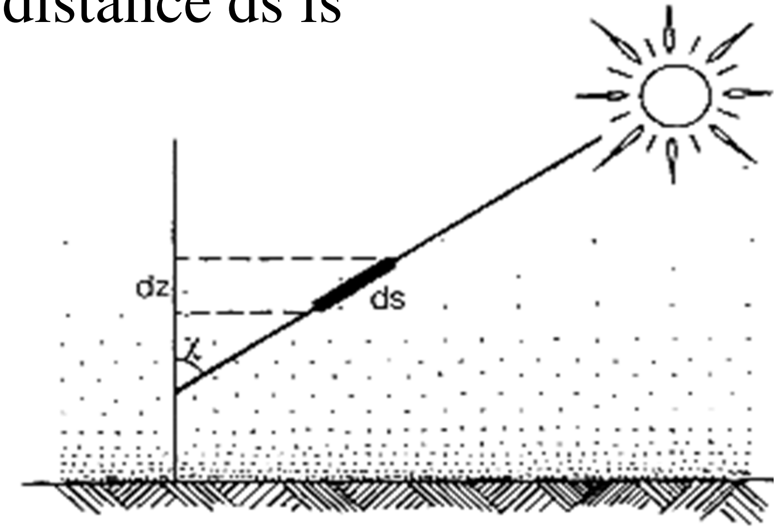
A Simple Model of the Ionosphere (where the "bumps" in the density profile come from)

- The atmospheric density decreases with height. If we let z be the height then our equation for the atmospheric density is where $n(z) = n_0 \exp(-z/H)$ $\quad H = kT/mg$
- The ionosphere is formed by ionization of atmospheric constituents mostly by electromagnetic radiation (UV radiation).
- The ionizing radiation comes from the Sun. If Φ_ν is the photon flux per unit frequency then the change in flux due to absorption by the neutral gas in a distance ds is

$$d\Phi_\nu = -n\sigma_\nu\Phi_\nu ds$$

where σ_ν is the photo absorption cross section (cm^2) and

n is the neutral density.



The Decrease in Photons

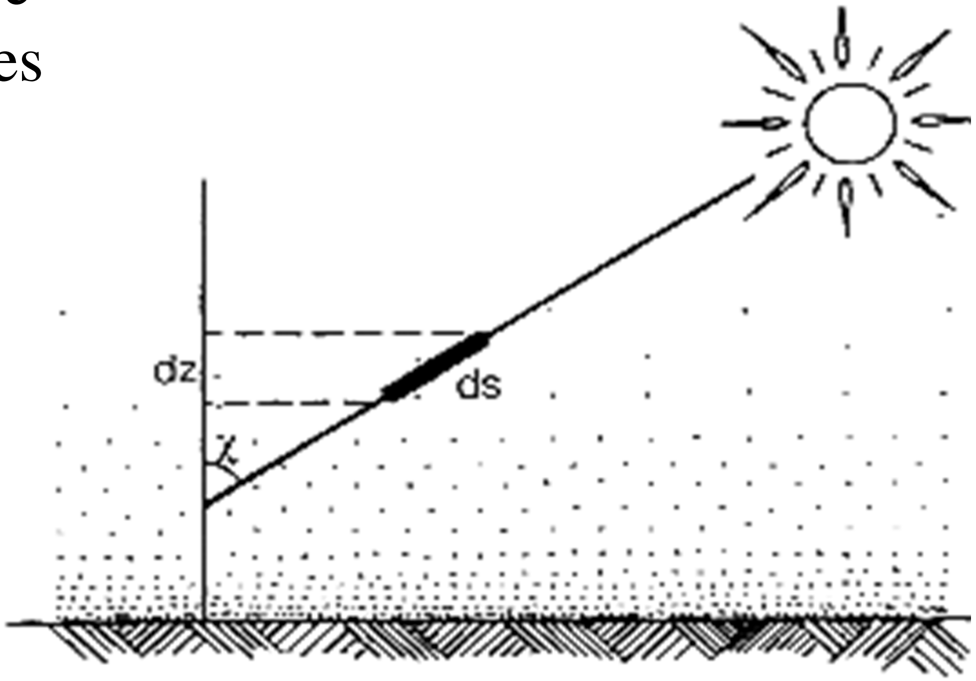
- The photon flux also has an exponential solution. After correcting for the angle of incidence of the sunlight, the solution becomes

$$\Phi_{\nu}(z) = \Phi_{\nu\infty} \exp(-\tau_{\nu})$$

where τ_{ν} is called the optical depth.

$$\tau_{\nu} = \sec\chi \sum_{t} \int_{z}^{\infty} \sigma_{\nu t} n(z')dz'$$

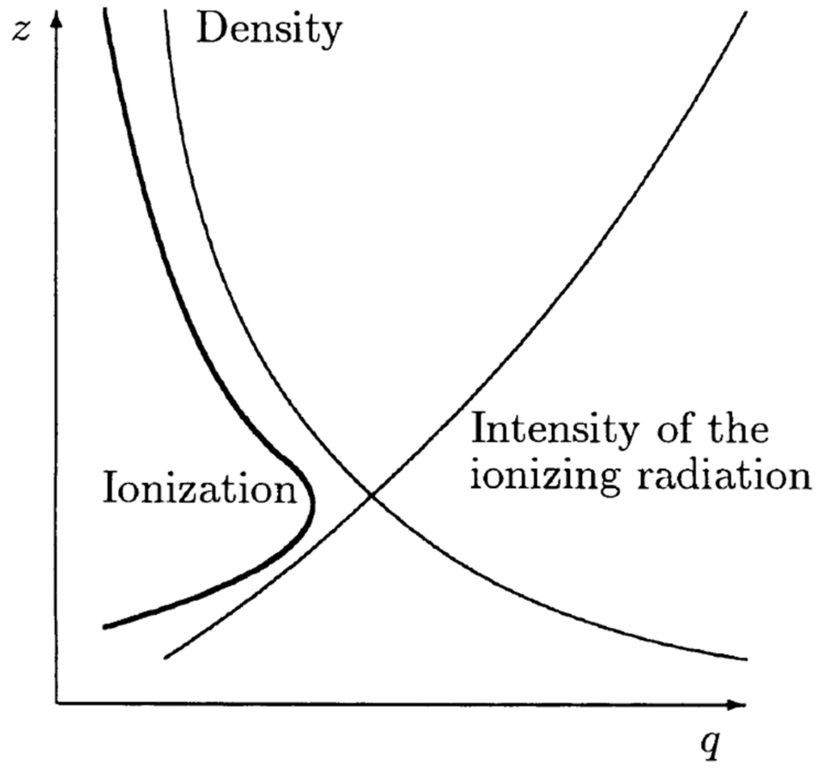
The summation allows us to include different atmospheric constituents.



Formation of Ionospheric Layers

- The number of photons is largest at the top of the ionosphere and decreases with decreasing altitude.
- The number of neutrals is largest at the bottom of the atmosphere and decreases with increasing altitude!
- Combining the two profiles gives the profile of a Chapman Layer
- The Chapman layer is the idealized height distribution of ionization as a function of height produced solely by absorption of solar radiation.
- The E and F1 regions are essentially Chapman layers
- Additional production, transport and loss processes are necessary to understand the D and F2 regions.

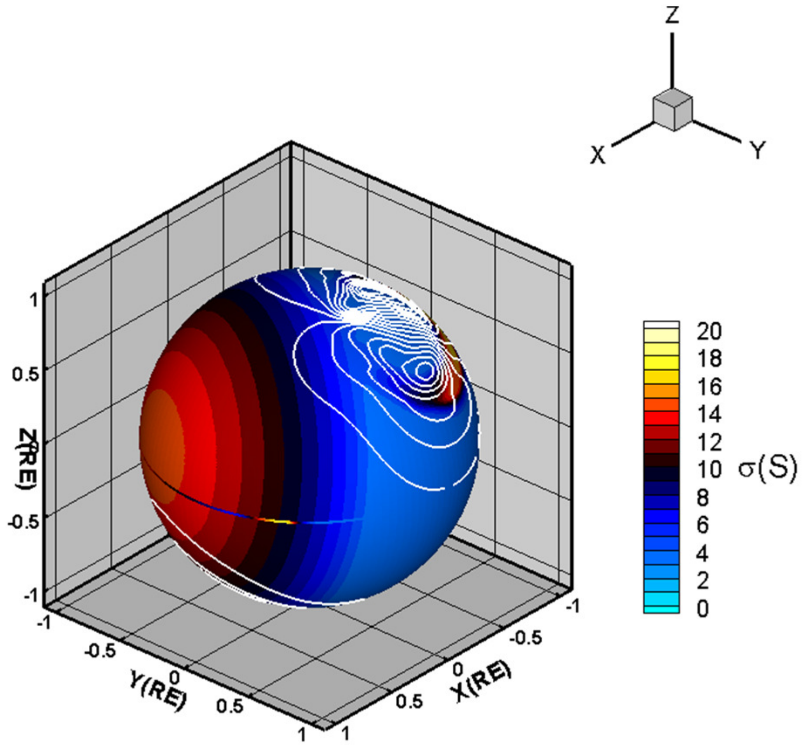
Forming a Chapman Layer



Kallenrode, 1998

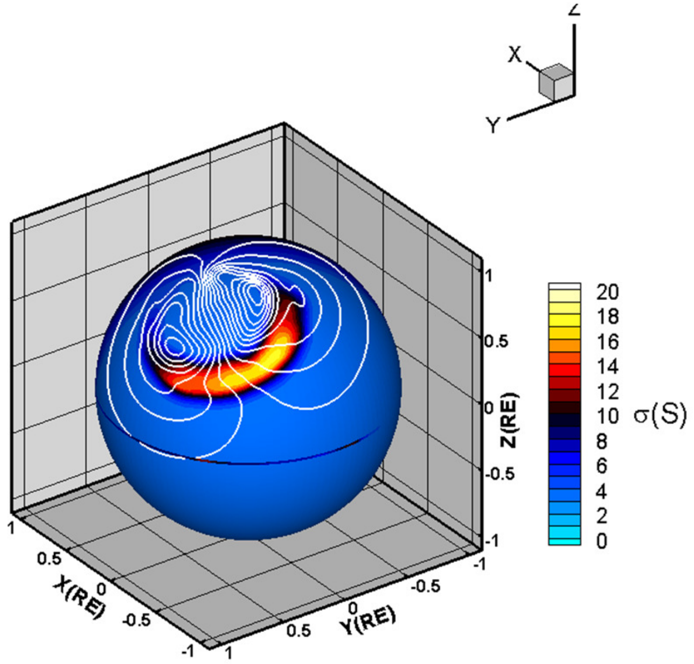
Ionospheric Conductivity

- The ionospheric conducts electricity.
- The conductivity of the ionosphere viewed from dusk.
- The conductivity is highest at noon and decreases toward night. This is an effect of UV ionization.
- At night there is a second form of ionization (electron impact ionization from precipitating electrons.



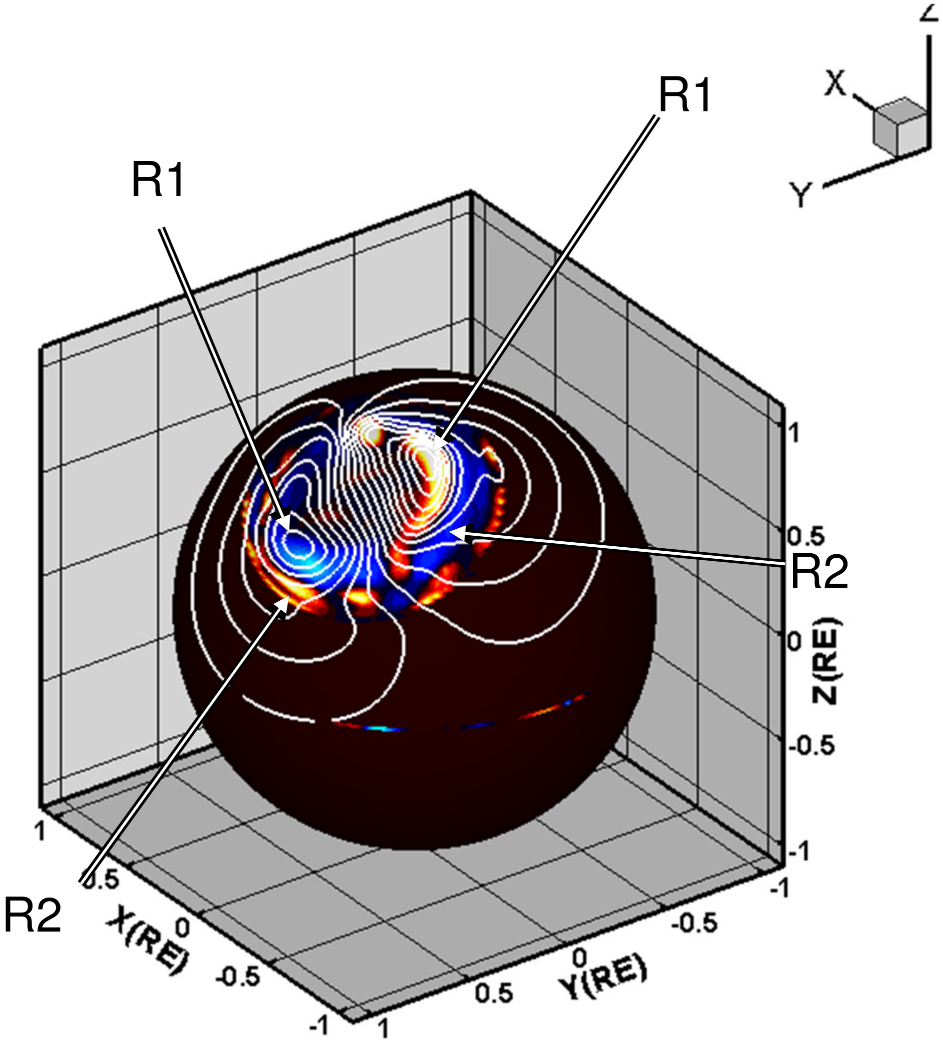
Ionospheric Conductance on the Night Side

- The enhanced conductivity on the night side is confined to the auroral oval (Y=0 is midnight).
- The white lines show the ionospheric convection (flow) pattern. Magnetic flux tubes from the magnetosphere move through the ionosphere. This shows the two cell pattern that occurs for southward IMF.
- Precipitation from the magnetosphere enhances conductivity especially during magnetic substorms and storms.



Field Aligned Currents

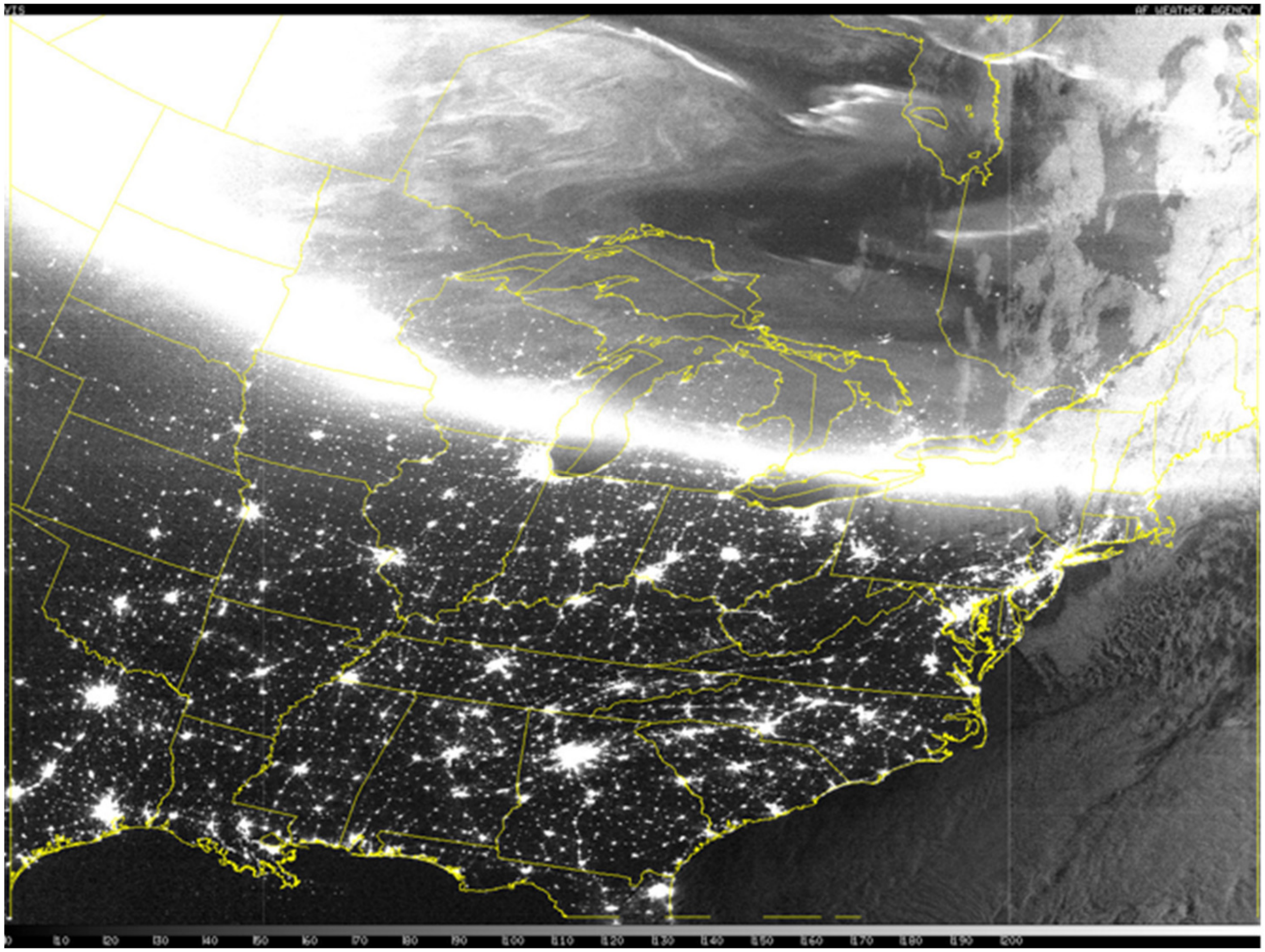
- Field aligned currents from the numerical simulation.
- Cold colors indicate currents away from the Earth and hot colors indicate currents toward the earth.
- The high latitude currents are caused by the vorticity of polar convection cells.



Field Aligned Currents and Aurora

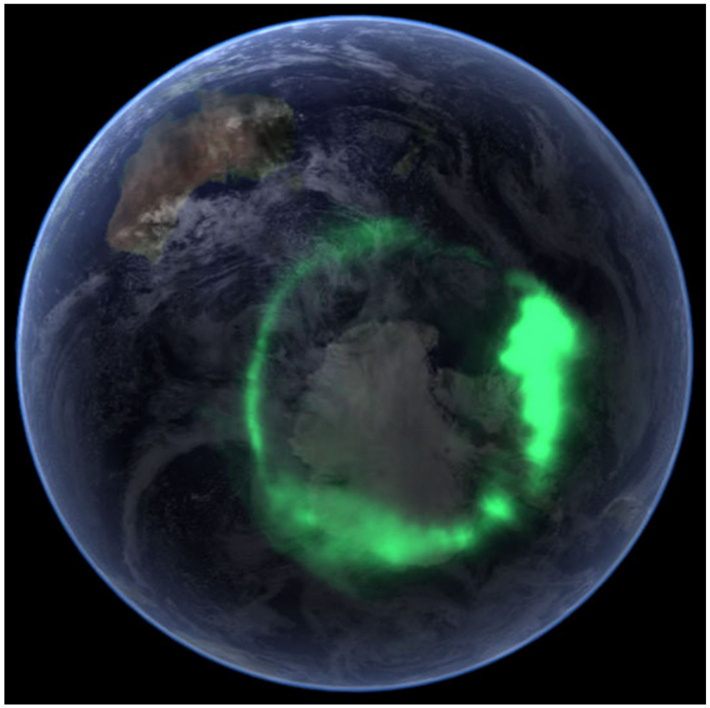
- By definition currents flow in the direction that protons move.

- Upward field aligned currents (electrons going down toward the Earth) create auroral emissions.



What are Aurorae?

- The aurora is mainly caused by excitation due to precipitating electrons and ions. Auroras typically are found at high geomagnetic latitudes where magnetospheric and solar wind electrons can readily access the upper atmosphere.
- Typically $10^{11} Js^{-1}$ (W) is required to maintain auroral emissions – this is well above the generating capacity of New Jersey ($2x10^{10}$ W).



Aurora australis (11 September 2005) as captured by NASA's IMAGE satellite, digitally overlaid onto the Earth composite image.

Auroral Light

- Auroral emissions are primarily due to a two-step process in which precipitating energetic auroral particles collide with the atoms and molecules of the Earth's upper atmosphere.
- Part of the particles kinetic energy is converted into energy stored in the chemically excited states of atmospheric species.
- The excited states relax giving off photons.
- The brightest visible feature of the aurora , the green line at 557.7nm is due to the transition of an electron from ^1S excited state to the ^1D state of atomic oxygen.
- Another commonly observed line particularly in the polar cusp and cap is the red line at 639 nm. This occurs as the ^1D state relaxes to the ground state ($^3P_2$).

Aurora images captured at midnight on April 10, 2015, in Delta Junction, Alaska. The aurora were likely connected to a minor to moderate geomagnetic storm that began late on April 9, 2015. The storm was triggered by a coronal mass ejection.

The Colors of the Aurora

- The 630nm emission forms the diffuse background radiation in which the discrete arcs are embedded.

- “Blood-red” auroras are produced by low-energy electrons (<<1 keV) they are found at high altitudes (>200km)

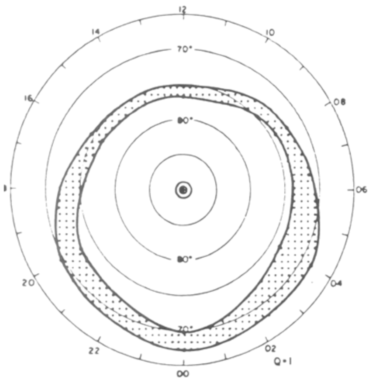
- “Red lower borders” indicate the presence of energetic particles (>10keV).

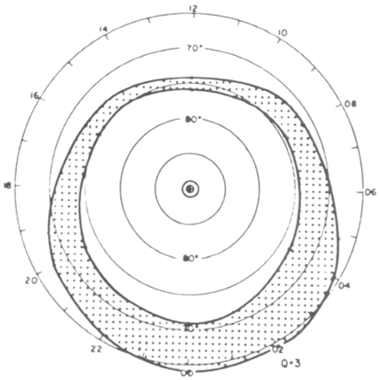
- Most auroras are yellow-green but sometimes appear gray (because our eyes are insufficiently sensitive)

- Magenta predominates below 100 km and is a combination of N^2 and O^+_2 emissions near 600nm and N^+_2 violet emissions.

The Auroral Oval

- The aurora are found in rings about the north and south poles.
- These are magnetically connected to the equatorial magnetosphere.
- The sketches on the right are based on observations and show the regions with aurora for quiet and disturbed times.


QUIET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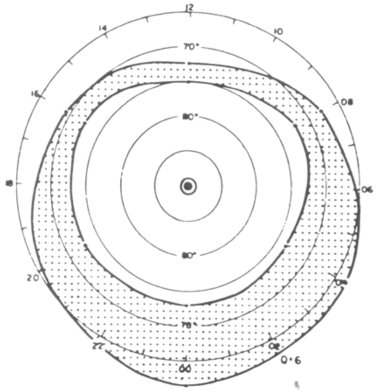
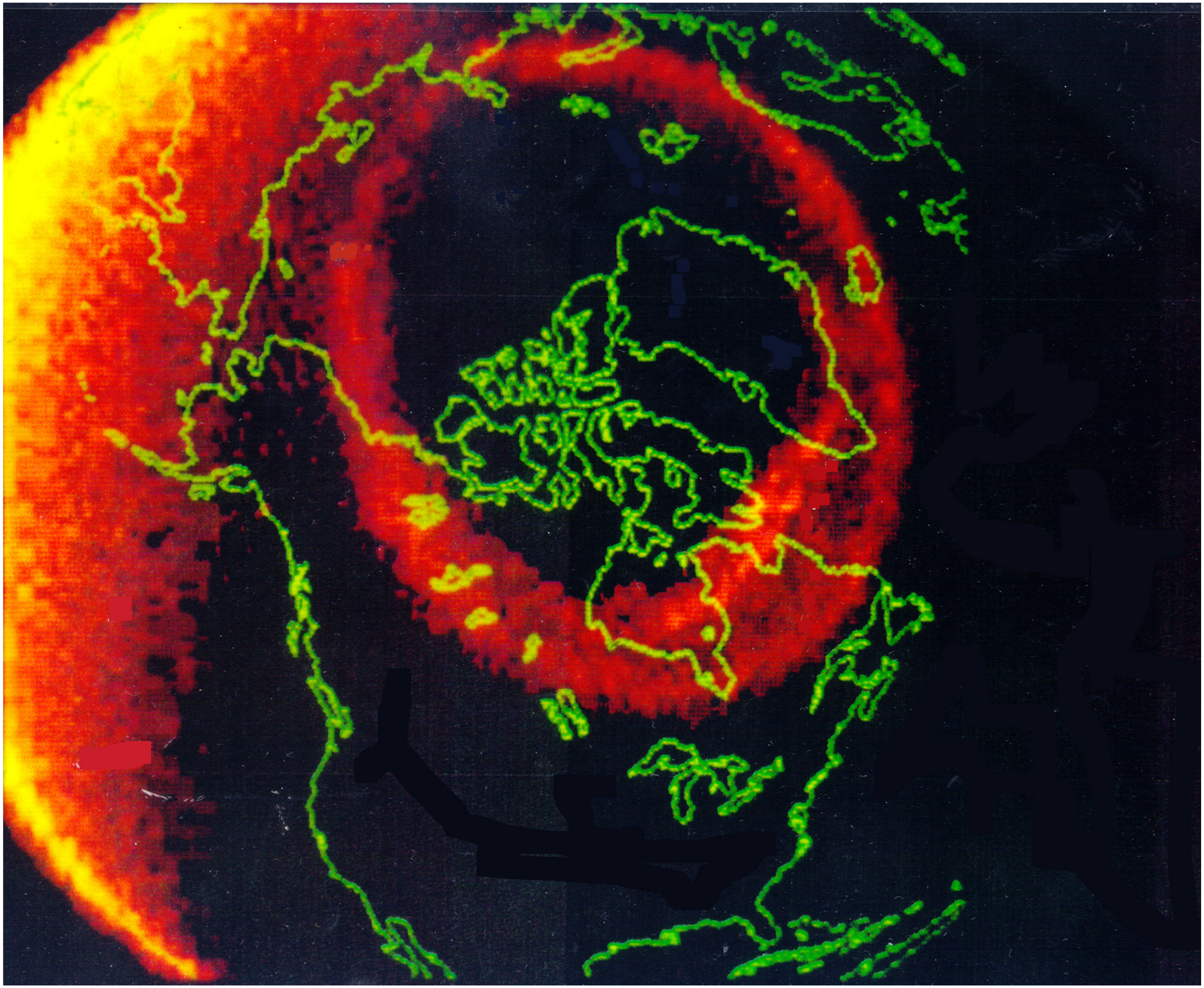

ACTIVE



[redacted]

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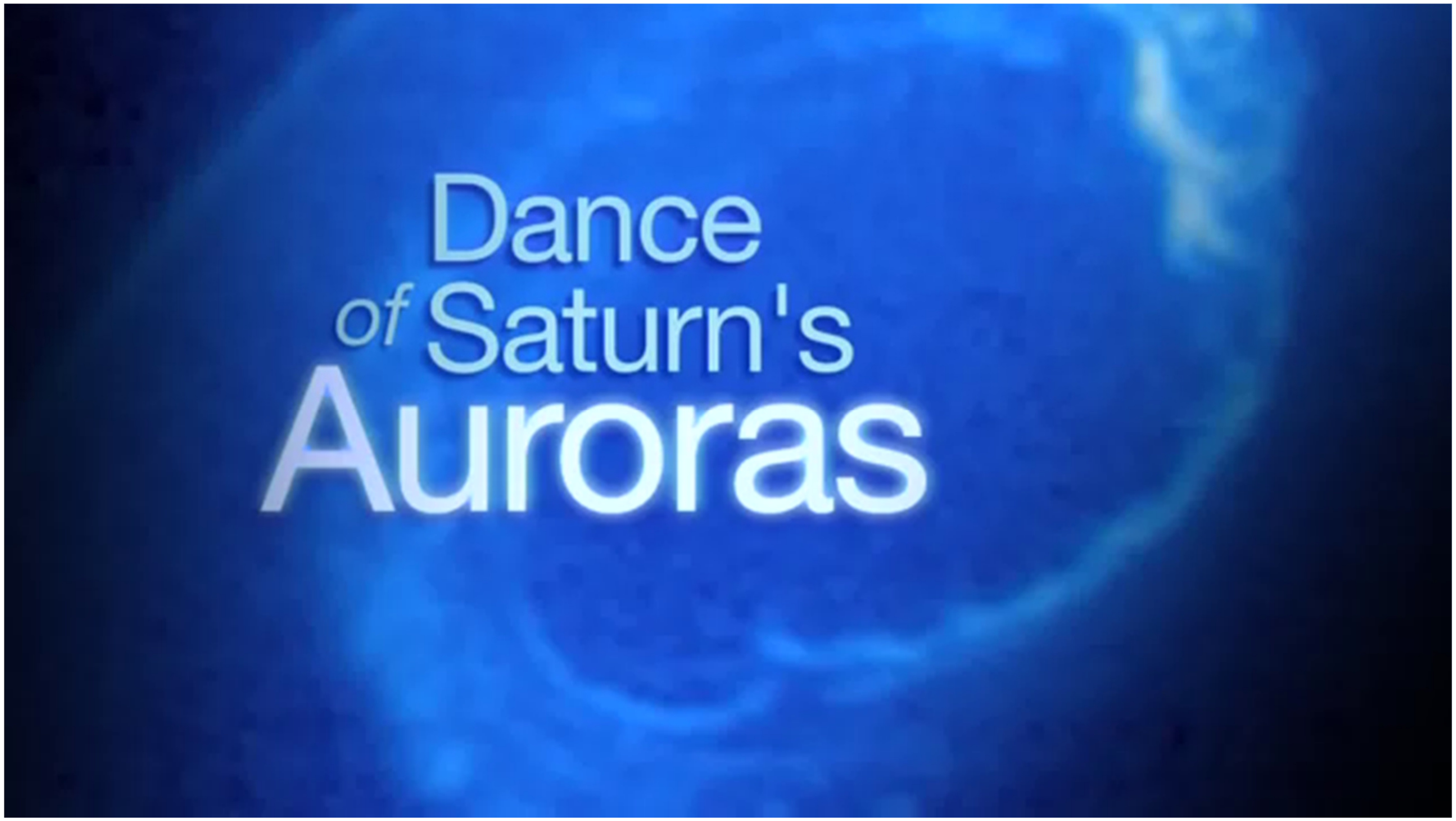
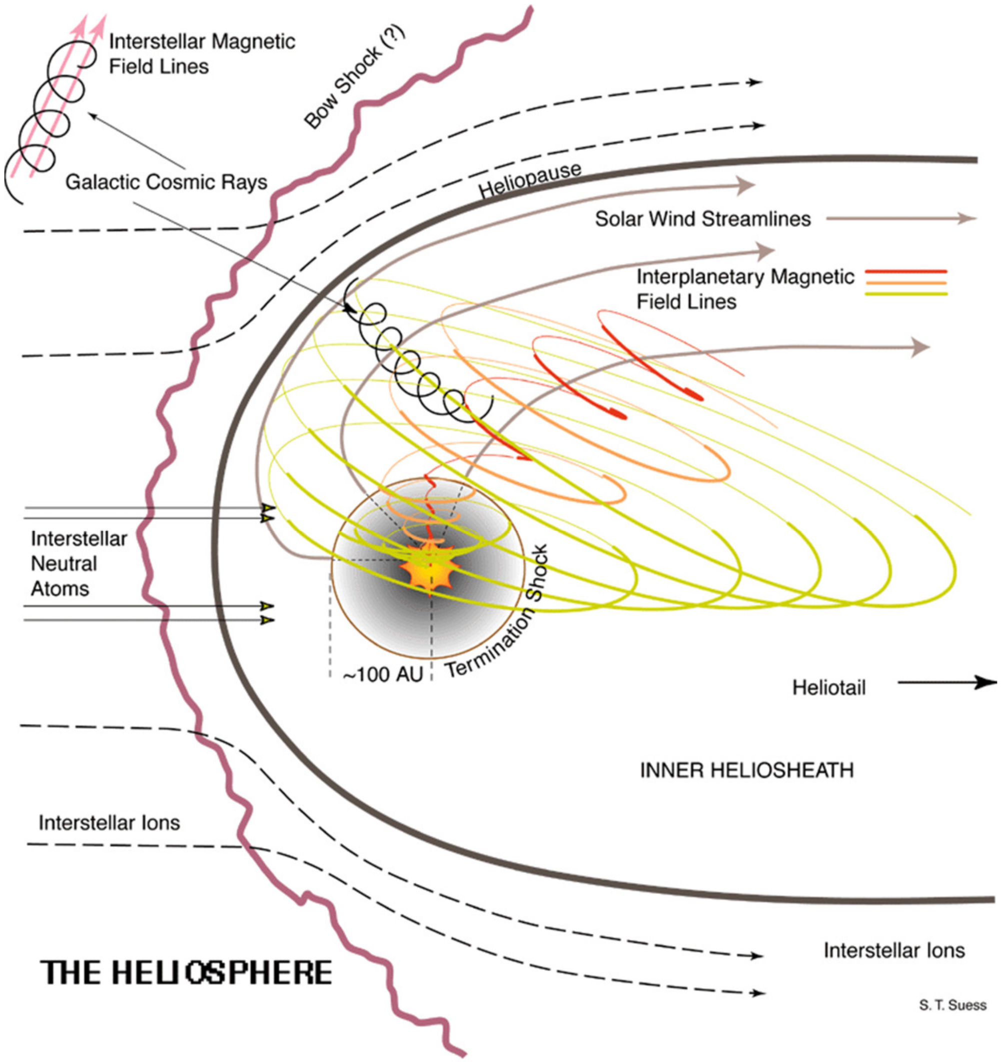
Aurora from ISS

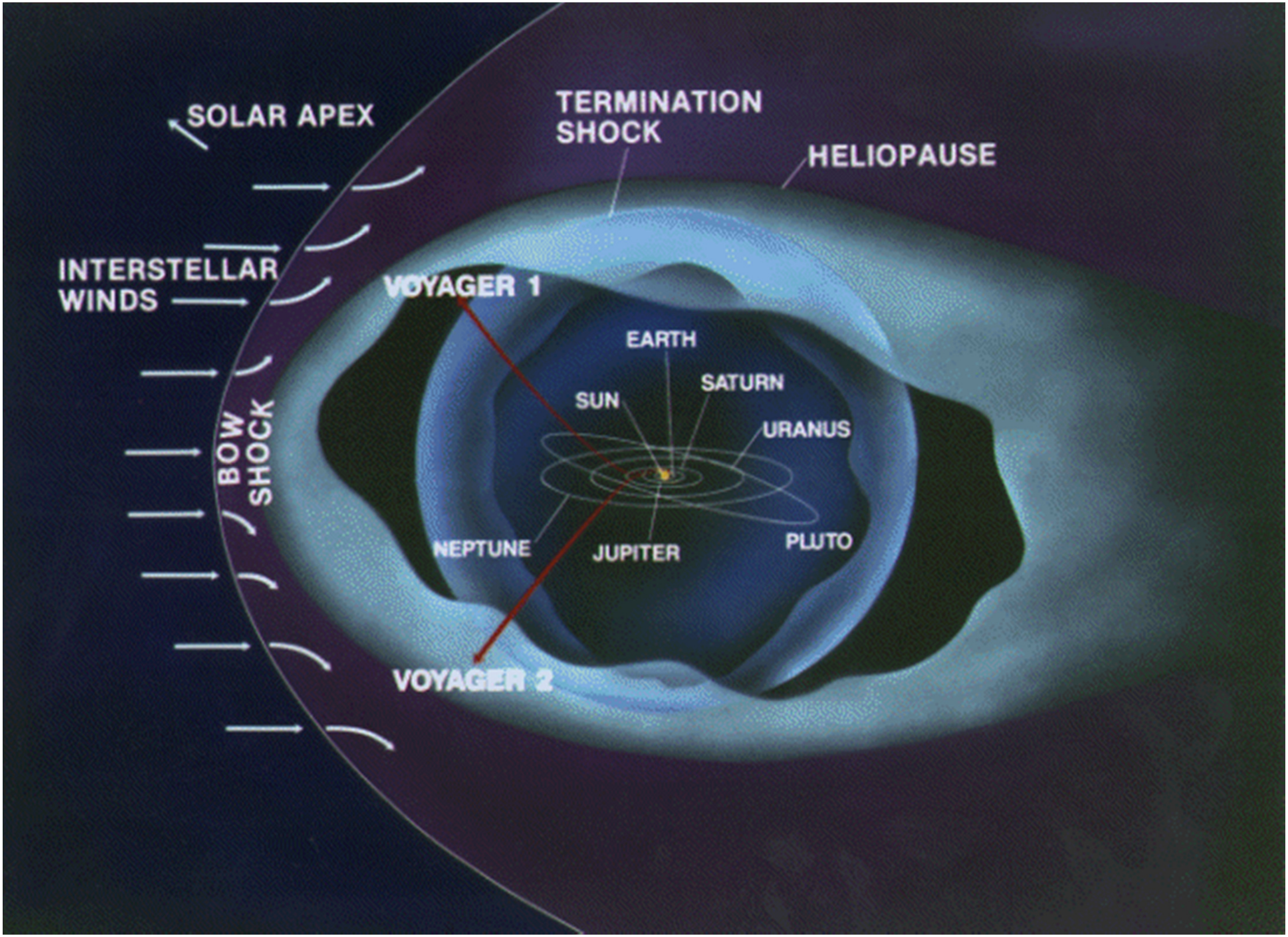
Auroras on Saturn.

Hubble Space Telescope, orbiting around Earth, was able to observe the northern auroras in ultraviolet wavelengths, and Cassini spacecraft, orbiting around Saturn, got complementary close-up views in infrared, visible-light and ultraviolet wavelengths.

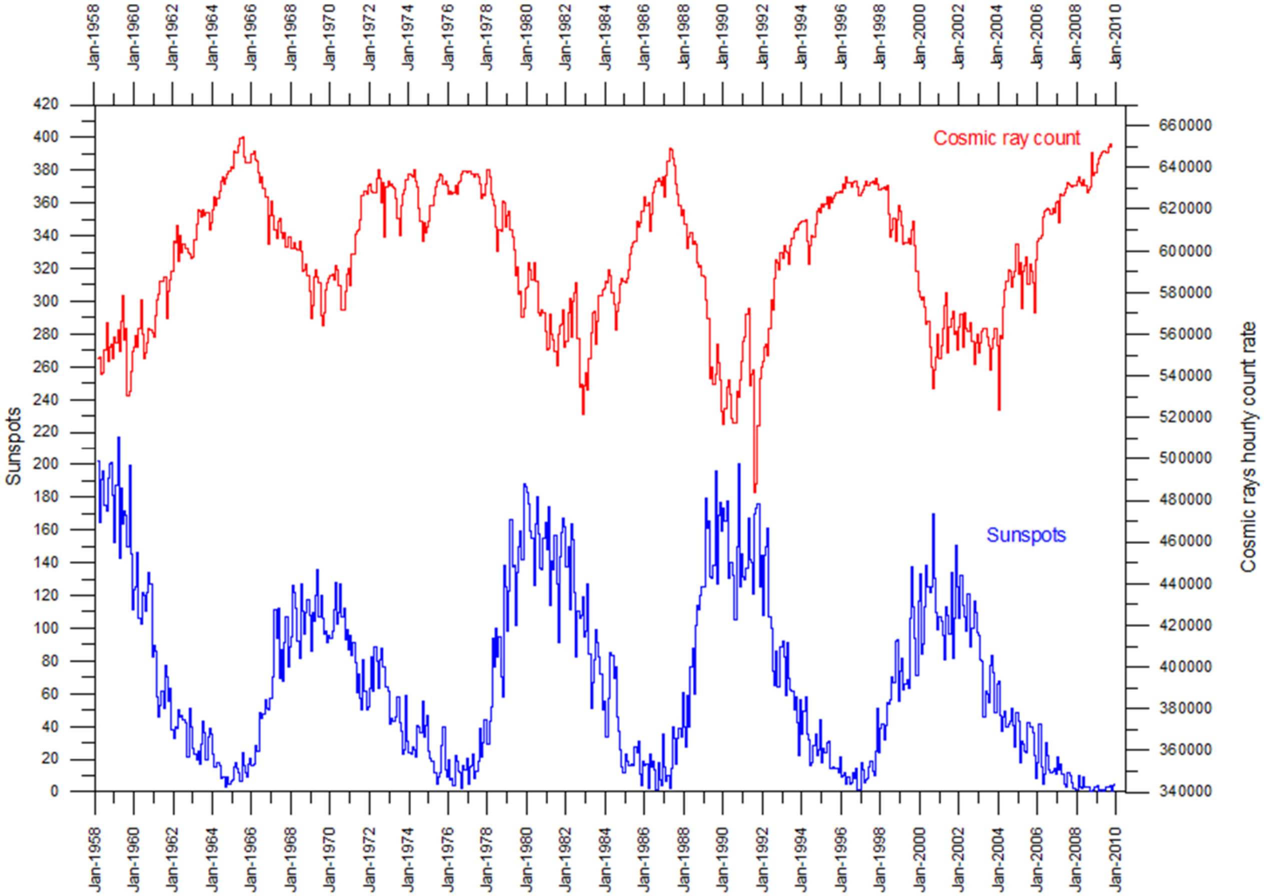


The Structure of Heliosphere



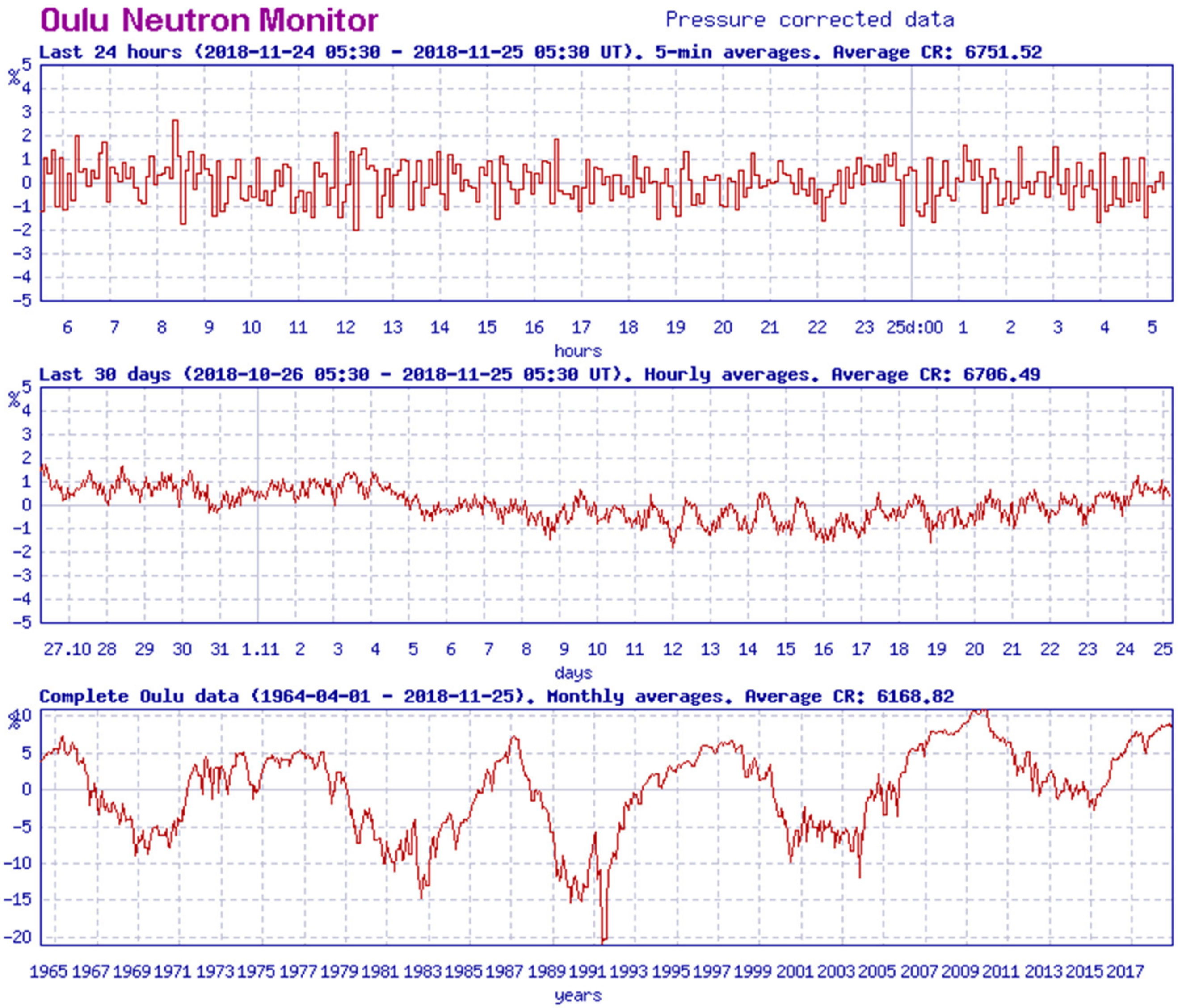

SOLAR APEX
TERMINATION SHOCK
HELIOPAUSE
INTERSTELLAR WINDS
VOYAGER 1
EARTH
SATURN
SUN
URANUS
BOW SHOCK
NEPTUNE
JUPITER
PLUTO
VOYAGER 2

Anti-correlation between the galactic cosmic ray flux and solar activity – Forbush effect



Forbush effect (1937) - a decrease in the intensity of cosmic rays as observed on Earth, attributed to magnetic effects produced by solar flares and CMEs. Forbush observed that the intensity of cosmic rays reaching Earth was inversely correlated with the 11-year solar cycle of sunspot activity, in that there are more cosmic rays at the minimum of the cycle and fewer cosmic rays at the maximum. At maximum solar activity, stronger magnetic fields are carried out into interplanetary space by the solar wind, and these fields block the cosmic rays.

Real-time observations of the cosmic ray flux by measuring neutron produced by the high-energy particles in the atmosphere.



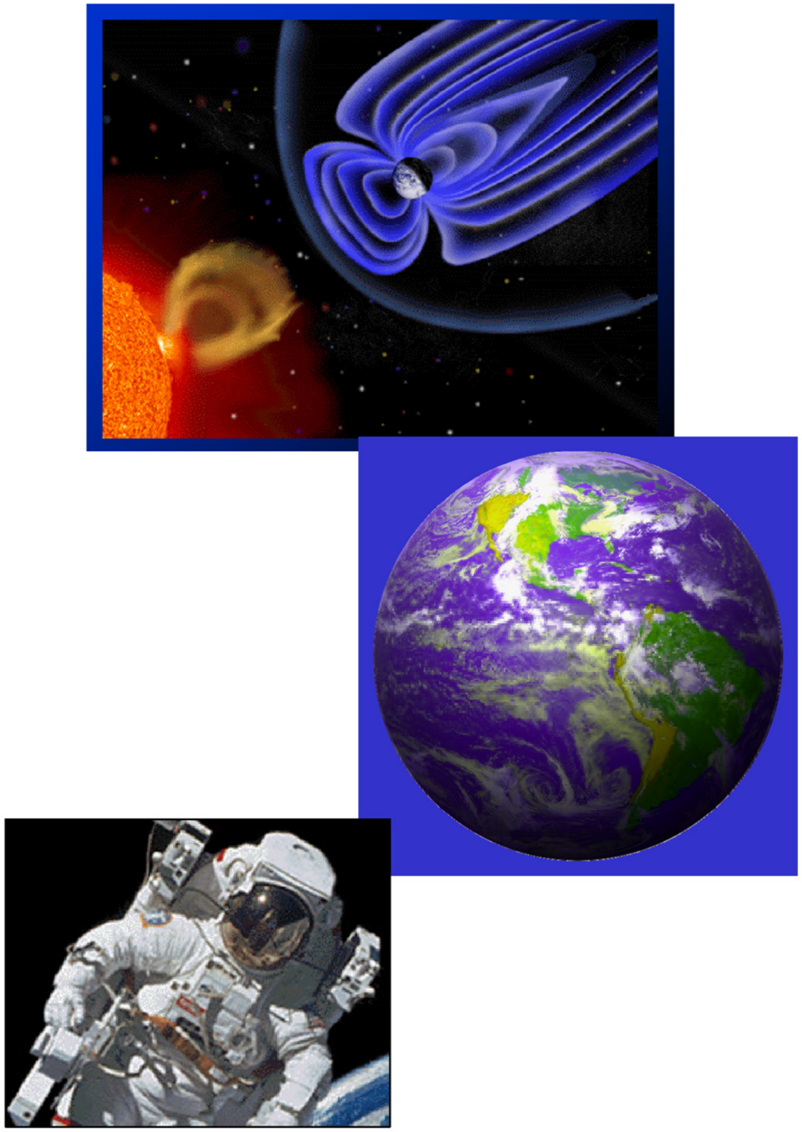
Living with a Star Program

Living With a Star (LWS) is a space weather-focused and applications-driven research program. Its goal is to develop the scientific understanding necessary to effectively address those aspects of the connected Sun-Earth system that directly affect life and society.

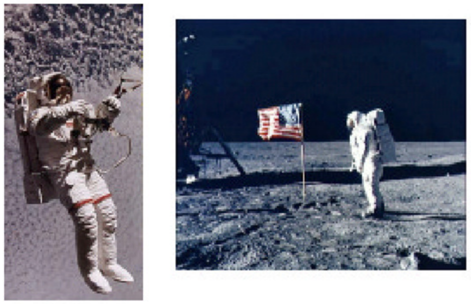
This program is a part of the Sun-Earth Connection (SEC) theme within the Office of Space Science.

Why Do We Care?

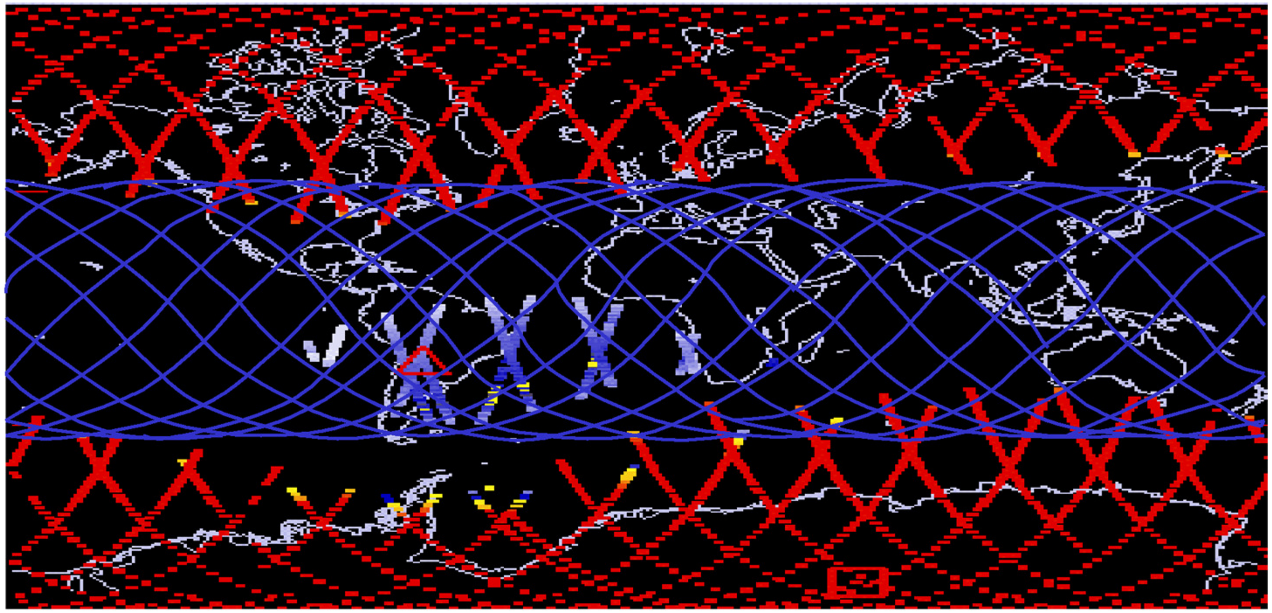
- **Solar Variability Affects Human Technology, Humans in Space, and Terrestrial Climate.**
- **The Sphere of the Human Environment Continues to Expand Above and Beyond Our Planet.**
  - Increasing dependence on space-based systems
  - Permanent presence of humans in Earth orbit and beyond



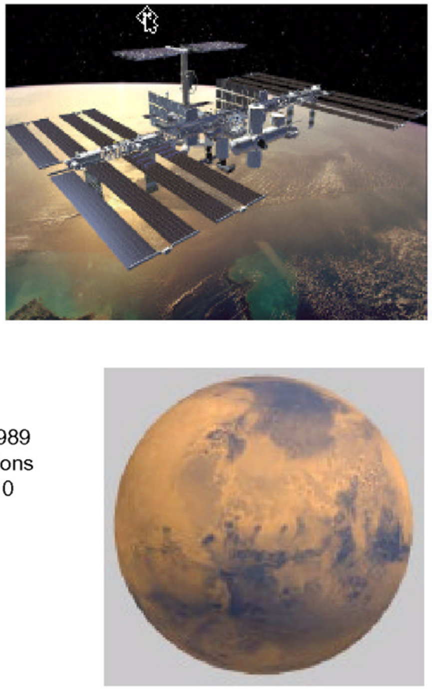
Solar Variability Can Affect Human Space Flight



- **Radiation Protection operations for future human missions (both to the ISS and to Mars) should be provided with observations of CME's from several vantage points, such as would be provided by SOHO and STEREO.** 1997 Workshop: "Impact of Solar Energetic Particle Events for Design of Human Missions", Houston, TX.
- **Space Station Orbit is Exposed to High Energy Solar Particles**



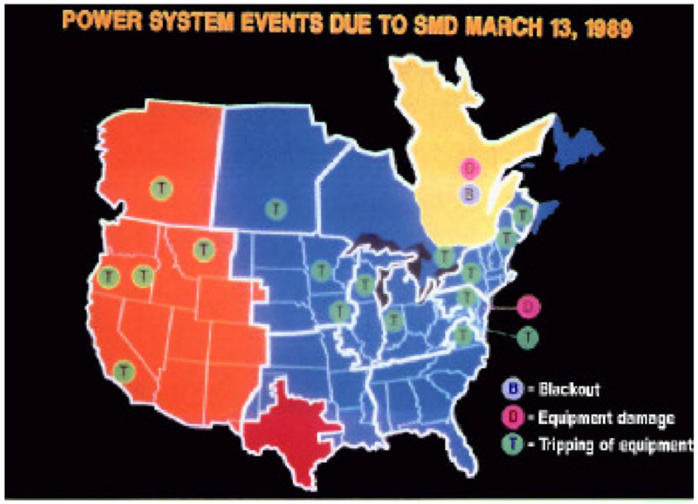
Oct 20, 1989
Solar Protons
NOAA-10

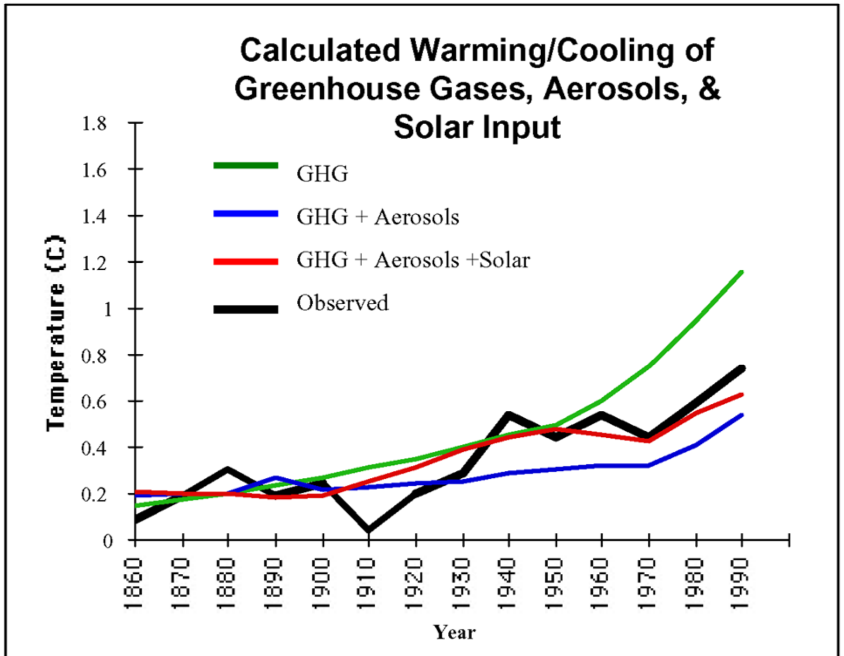


Issue: Requires focused research effort to improve knowledge about risk levels and possible risk mitigation techniques. Enabling research for human voyages beyond Earth.

Solar Variability Can Affect Where We Live

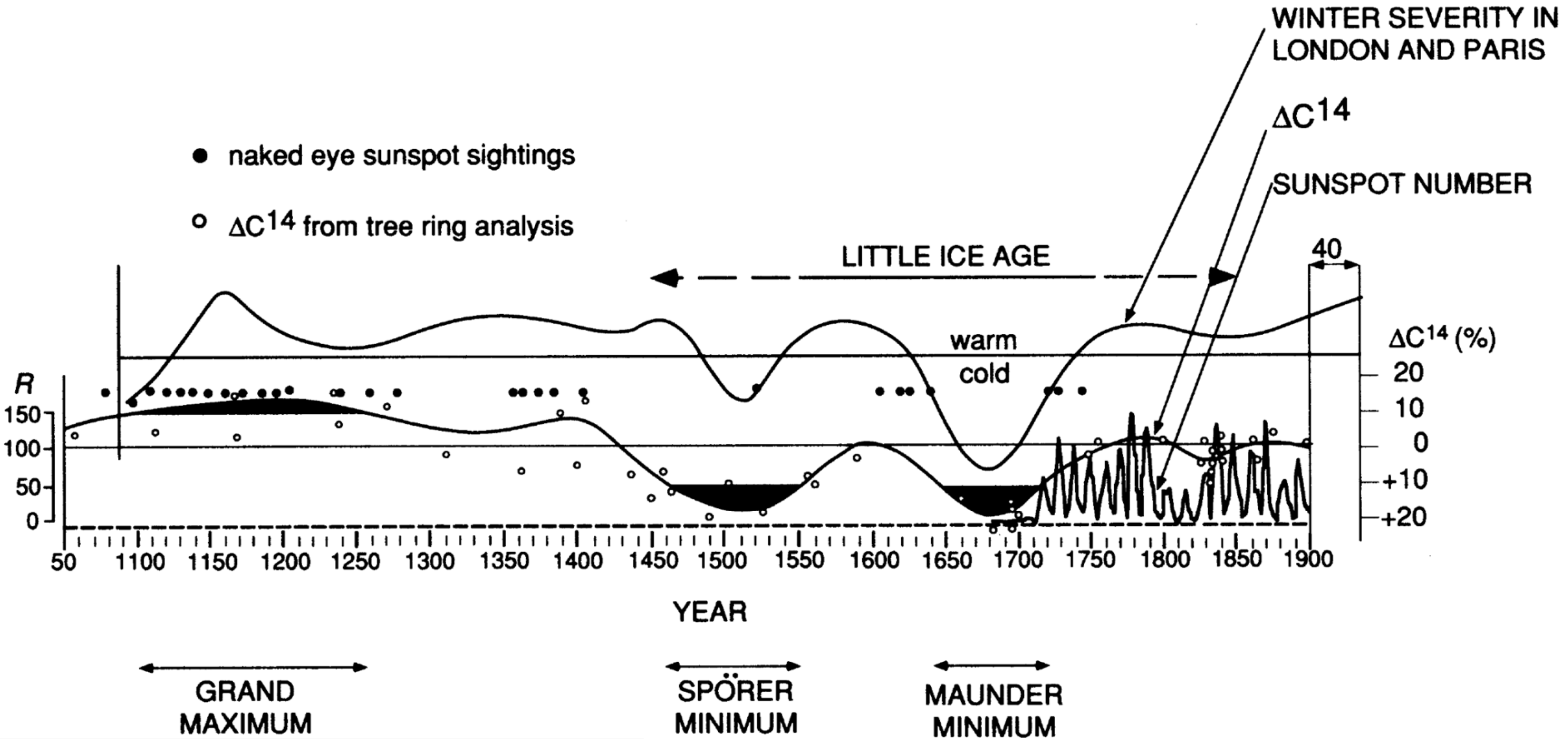
- **Electric grid disruption and power transformer damage.**
- **GPS signals, high frequency (HF and VHF) radio communications, and long range radar.**
- **Microelectronics and humans in high altitude aircraft.**
- **Telecommunication cables.**
- **High precision electronic chip fabrication.**
- **Terrestrial climate.** ***"The Sun's fingerprints are showing up all over the climate records. The 11- and 22-year sunspot cycles have turned up in other analyses of ocean temperatures and in ice cores...."*** Science, March 8, 1996





Curves based on Wigley et al. calculations (1997)

Solar Variability Can Affect Terrestrial Climate



During the Little Ice Age, London's Thames River froze in winter, something that no longer happens. This 19th century engraving depicts the annual Frost Fair held on the ice-bound river, this one during the winter of 1683-84.

Given the massive economic impact of small changes in climate, we should fully understand both natural and anthropogenic causes of global change.

What can we do about it?

Goals of the Sun-Earth Connection Initiative

1. **Quantify physics, dynamics, and behavior of Sun-Earth connected system through the range of conditions occurring in the 11 year solar cycle.**
    - **Obtain improved measurements.**
    - **Better understand Sun-Earth disturbances.**
    - **Understand the solar cycle.** ***For long-range forecasting & assessing solar role in climate change.***
2. **Develop predictive models for the system that:**
    - **Demonstrate understanding of physics.**
    - **Have utility for prediction of space weather.**
3. **Minimize impact of space weather on technology and human space flight.**
    - **Determine space environmental conditions vs location, time in solar cycle.** ***Needed for design of systems to minimize sensitivity to space weather.***
    - **Develop improved techniques for space weather conditions including SPE & their access to ISS and at locations of human explorers in deep space.**
    - **Fly low cost flight test beds for validation of rad-hard, rad-tolerant systems.**

Apply a systems approach.

Heliophysics System Observatory

- *17 Operating Missions with 24 Spacecraft*
- *4 Missions in Development*
- *1 Mission in Formulation*

🟨 Formulation
🟧 Implementation
🟩 Primary Ops
🟦 Extended Ops