ESS 7
Lectures 15 and 16
October 31 and November 2, 2011
The Atmosphere and Ionosphere
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 aurora 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).
We live in the region called the troposphere. In this course we will call our familiar weather ‘tropospheric weather’. The lower regions of Earth’s atmosphere are characterized by an N/O composition with small amounts of H₂O, Ar, CO₂. The green house effect allows life to live on Earth, otherwise it would be too cold!
The Structure of the Atmosphere

- Note that the troposphere is a thin layer at the bottom. Above it is the stratosphere and jets often fly in the lowest part of the stratosphere.

- The temperature decreases with altitude in the troposphere, rises in the stratosphere, and again falls in the mesosphere, where the minimum temperatures are found.

- The lowest part of the thermosphere above is the ionosphere.
The Different Regions

- 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)
Why does the Earth have an Atmosphere?

• Why does the Earth have an atmosphere while other planets like Mercury or the Moon have none?
• The pressure gradient in the atmosphere points toward the Earth.
• That means that the force is outward toward space

\[ \vec{F}_P = -\nabla P \]

• The ideal gas law gives \( PV=nRT \) where \( P \) is the pressure, \( V \) is the volume, \( n \) is the number of moles of gas, \( R \) is the gas constant (8.3145 J K\(^{-1}\)mol\(^{-1}\)) and \( T \) is the temperature.
• This is equivalent to \( P=nkT \) where \( n \) is the number density, \( k \) is the Boltzman constant and \( T \) is the temperature.
Why the Earth has an Atmosphere

- Compared to space the pressure is much greater in the atmosphere.
- Why then doesn’t the atmosphere simply go out into space?
- The answer is that the atmosphere is roughly in hydrostatic equilibrium with gravity – the pressure force is balanced by the force of gravity

\[ \nabla P = -\rho g \]

where \( \rho \) is the mass density (mass/volume) and \( g \) is the gravitational acceleration (equal to 9.8 m s\(^{-2}\) at the Earth’s surface.)
A Model of the Earth’s Atmosphere

• The density decreases as a function of height

\[ n(\text{height}) = n_0 \exp\left(-\frac{\text{height}}{H}\right) \]

where height is the altitude above the Earth and \( H \) is a “scale height” and \( n_0 \) is the density at the surface.

• The scale height is given by \( H = kT/mg \) \( k \) is the Boltzman constant, \( T \) is the temperature, \( m \) is the average mass of the atmospheric constituents, and \( g \) is gravity.

• The density of the atmosphere falls off rapidly with height.

• Mercury and the Moon don’t have atmospheres because they are not massive enough to hold them.
Exponential Decrease (Decay)

Exponential Decay is frequently found when the “rate” is proportional to the “amount”. On a semilog graph it is a straight line.
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 300Km 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-Heaviside 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 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 particles (particles whose mirror altitude is in the atmosphere) also ionize particles.
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.
<table>
<thead>
<tr>
<th>Region</th>
<th>Primary Ionospheric Regions</th>
<th>Altitude</th>
<th>Peak</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>60-90 km</td>
<td>90 km</td>
<td>$10^8 - 10^{10}$ m$^{-3}$</td>
</tr>
<tr>
<td>D</td>
<td></td>
<td>90-140 km</td>
<td>110 km</td>
<td>Several x $10^{11}$ m$^{-3}$</td>
</tr>
<tr>
<td>E</td>
<td></td>
<td>140-200 km</td>
<td>200 km</td>
<td>Several $10^{11}$-10$^{12}$ m$^{-3}$</td>
</tr>
<tr>
<td>F1</td>
<td></td>
<td>200-500 km</td>
<td>300 km</td>
<td>Several x $10^{12}$ m$^{-3}$</td>
</tr>
<tr>
<td>F2</td>
<td></td>
<td>above F2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Topside</td>
<td></td>
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</tbody>
</table>
• 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 to $O^+$
- 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 $\text{N}_2$, $\text{O}_2$, and $\text{O}$.
  – 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 Come From

- The atmospheric density decreases with height. If we let \( z \) be the height then our equation for the atmospheric density is

\[
n(z) = n_0 \exp\left(-\frac{z}{H}\right)
\]

where \( H = kT/mg \)

- The ionosphere is formed by ionization of atmospheric constituents mostly by electromagnetic radiation (UV radiation).

- The ionizing radiation comes from the Sun. If \( \Phi_\nu \) 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 \( \sigma_\nu \) is the photo absorption cross section (m\(^2\)) and \( n \) is the neutral density.
The Decrease in Photons

- This too has an exponential solution. After correcting for the angle of incidence of the sunlight, the solution becomes

\[ \Phi_v(z) = \Phi_{v\infty} \exp(-\tau_v) \]

where \( \tau_v \) is called the optical depth.

\[ \tau_v = \sec \chi \sum \int_{z'}^{\infty} \sigma_{vt} n(z') dz' \]

The summation allows us to include different atmospheric constituents.
Forming a Chapman Layer

- 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.

Kallenrode, 1998
A Simple Chapman Layer

- The vertical profile in a simple Chapman layer is

\[ n_e = \sqrt{\frac{S_0}{\alpha}} \exp \left( \frac{1}{2} - \frac{z}{2H} - \frac{\sec \chi}{2} \exp \left[ -\frac{z}{H} \right] \right) \]

where \( \alpha \) accounts for recombination

- The E and F₁ regions are essentially Chapman layers

- Additional production, transport and loss processes are necessary to understand the D and F₂ regions.
Moving charges form an electrical current

\[ I = nqv \]

In plasma usually both electrons and ions move

\[ I = n_i e v_i - n_e e v_e \]

More particles more \( I \)

More speed more \( I \)

Negative charge going right gives a current going left!
Ionospheric Conductance

- 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 simulation in the previous calculation.
- 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.
Region 1 and Region 2 Currents

- The Region 1 and Region 2 currents are in green.
- They close in the magnetosphere.
- The Region 2 currents close in the inner magnetosphere and ring current regions.
- The Region 1 currents close in the outer magnetosphere.
The Polar Wind

• Within the high latitude magnetosphere (auroral zone and polar cap) plasmas undergo a circulation cycle.
  – At the highest latitudes the geomagnetic field lines are “open” in that only one end is connected to the Earth.
  – Ionospheric plasma expands freely in the flux tube as if the outer boundary condition was zero pressure.
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.
February 17, 2010 Auroras

One man’s source of particles to make conductivity is another man’s poetic soliloquy!

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