Introduction to the Ionosphere

Anthea J. Coster
MIT Haystack Observatory
References


- Brekke, A. Physics of the Upper Atmosphere, John Wiley & Son, 1997

Figure 1. The Sun-Earth system. Energy in various forms is constantly flowing from the Sun to Earth. Dynamo action in the convection zone drives variations in this energy flow by producing sunspots and bright active regions. Photons from the Sun’s surface and atmosphere reach Earth’s surface and atmosphere, but particles and fields that together form the solar wind are intercepted by the magnetosphere (blue). Eruptive events such as coronal mass ejections, shown emerging from the Sun’s atmosphere into the solar wind, perturb the magnetosphere and allow energetic particles to penetrate Earth’s atmosphere in the polar regions, where the magnetic field lines are anchored. (Figure not to scale.)
Earth’s Upper Atmosphere (and most of the Solar System): Is a Natural Plasma

• Plasma is the fourth state of matter

• The universe is filled with plasma

• Extreme ultraviolet output from the Sun creates a plasma in Earth’s upper atmosphere through ionization
1. Ionosphere – What is it? Where is it? Why do we care? (Provide answers in chat!)
Structure of the Ionosphere

- **D-region**
- **E-region**
- **F-region**
- **Topside**

**IRI-95 Electron Density**

**IRI-95 Ion Species Density**

- $H^+$
- $O^+$
- $NO^+$

**AM radio transmitter**

- E layer 180 km
- E layer 120 km
- D layer 60 km

**Night Time**
- F Layer

**F Layers** Combine at Night

**E Layer Almost Disappears at Night**

**D Layer Disappears at Night**
The Discovery of the Ionosphere

1902 AD - Oliver Heaviside
Predicts layer of ionized gas between 90 and 150 km

1924 AD – Edward Appleton
Measurement of ionospheric reflecting layer height
BBC Bournemouth Transmitter to Cambridge
Frequency change method

1925 AD – Gregory Breit and Merle Antony Tuve
Height of the Ionosphere with Seasonal and Diurnal variations
Pulse sounding technique

1926 AD - Robert Watson-Watt introduces the name “Ionosphere”
Radio Waves and Propagation

Waves are described by:

- Wavelength, Amplitude, Polarization
- Phase and Direction of Propagation
- Propagate at the speed of light (in the medium)
- Can be superimposed linearly (mostly true)

Maxwell's Equations

\[
\begin{align*}
\nabla \cdot D &= \rho \\
\nabla \cdot B &= 0 \\
\n\nabla \times E &= -\frac{\partial B}{\partial t} \\
\n\nabla \times B &= \mu_0 \frac{\partial D}{\partial t} + \mathbf{J}
\end{align*}
\]
Radio Propagation in the Ionosphere

Index of Refraction (no \(B\) field)

\[ n^2 = \frac{c^2 k^2}{\omega^2} = 1 - \frac{\omega_p^2}{\omega^2} \]

Plasma Frequency

\[ \omega_p^2 = \frac{n_0 e^2}{m \varepsilon_0} \]

Phase Velocity

\[ V_{ph} = \frac{\omega}{k} \]

Topside
F region peak
E region
D region
Absorption

Significantly Above Critical Frequency

Above Critical Frequency

Ducting

Multiple Hops

Below Critical Frequency

[Hurricane Felix, NASA]
Magnetic Field Effects on Propagation

Charged particles gyrate around B-field and drift perpendicular due to applied forces.

\[ \frac{m \, dv}{dt} = q(E + v \times B) \]

\[ \omega_c = \frac{qB}{m} \]

\[ k \parallel B \]

\[ \beta = RM \lambda^2 \]

\[ RM = \frac{e^3}{8\pi^2 \epsilon_0 m^2 c^3} \int_0^d n_e B \cdot dS \]
Index of Refraction \( n = \frac{c}{v_p} \) in the Ionosphere

\[
n^2 = 1 - \frac{X(1 - X)}{(1 - X) - \frac{1}{2} Y_T^2 \pm \left(\frac{1}{4} Y_T^4 + (1 - X)^2 Y_L^2\right)^{1/2}}
\]

where
\( n \) is the index of refraction

\[
X = \frac{\omega_N^2}{\omega^2} \\
Y = \frac{\omega_H}{\omega} \\
\omega_N = \left(\frac{Ne^2}{\varepsilon_0 m_e}\right)^{1/2} \\
\omega_H = \frac{e|B|}{m_e}
\]

\( \omega \) = the angular frequency of the radar wave,

\( Y_L = Y \cos \theta, \quad Y_T = Y \sin \theta, \)

\( \theta \) = angle between the wave vector \( \vec{k} \) and \( \vec{B} \),

\( \vec{k} \) = wave vector of propagating radiation,

\( \vec{B} \) = geomagnetic field, \( N \) = electron density

\( e \) = electronic charge, \( m_e \) = electron mass,

and \( \varepsilon_0 \) = permittivity constant.
Illustration of Atmospheric Effects

Elevation Refraction

Range Delay

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• **Ionosphere**

In the solar wind plasma, and in many parts of the magnetosphere the ionization degree is 100%.

What is the maximum ionization degree in the ionosphere?

• **Ionosphere**

At maximum 1% of the neutral atmosphere is ionized.
2. What is the ionosphere made of?

What are Scale Heights?

Why are there Different regions (D/E/F - importance of different processes in different regions)?

How does it form? What are the primary mechanisms of Production and Loss?
Distinct Regions in the Ionosphere Form because:

The Solar spectrum deposits its energy at various heights depending on the absorption characteristics of the atmosphere.

The physics of recombination depends on the atmospheric density which changes with height.

The composition of the atmosphere changes with height.
Photoionization
A scale height is a term often used in scientific contexts for a distance over which a quantity decreases by a factor of $e$. It is usually denoted by the capital letter $H$.

For planetary atmospheres, it is the vertical distance upwards, over which the pressure of the atmosphere decreases by a factor of $e$. The scale height remains constant for a particular temperature. It can be calculated by

$$H = \frac{kT}{Mg}$$

where:

$k$ = gas constant = 8.314 J·(mol K)$^{-1}$

$T$ = mean molecular temperature in kelvins

$M$ = mean molecular mass of dry air (units kg·mol$^{-1}$)

$g$ = acceleration due to gravity on planetary surface (m/s$^2$)
The Neutral Atmosphere (according to NRLMSISE-00)
Composition

At heights over 100 km, molecular diffusion means that each molecular atomic species has its own scale height.

**Dominant Constituent**

0-200 Km  |  Nitrogen
200-1000 Km  |  Oxygen
1000-2500 Km  |  Helium
2500 – 8-14 Earth Radii  |  Hydrogen
Hydrostatic Equilibrium

- The force of gravity on a parcel of air is balanced by the pressure gradient

\[ n_n m_n g = - \frac{dp}{dh} = - \frac{d}{dh} (n_n k T_n) \]

- Assume \( T_n \) is independent of height and integrate we obtain

\[ n_n = n_0 \exp \left[ - \frac{(h - h_0)}{H_n} \right] \]

- The density of an atmosphere falls off (generally) exponentially.
Ionospheric Density Profile

- Photochemical equilibrium assumes transport is not important so local loss matches local production.
  \[ \frac{\partial n_e}{\partial t} = Q - L = 0 \]

- If loss is due to electron-ion collisions, we get a Chapman layer
  \[ Q = L = \alpha n_e^2 \]
  \[ n_e = \left( \frac{Q}{\alpha} \right)^{\frac{1}{2}} \]

- If there is vertical transport
  \[ \frac{\partial n_e}{\partial t} = Q - L - \frac{\partial (n_e u_{eh})}{\partial h} \]

- Treating the pressure forces of electrons and ions and assuming neutrals are stationary, we obtain
  \[ n_i u_{pl} = -D \left[ \frac{dn_e}{dh} + \frac{n_e}{H_p} \right] \]

- Where \( D = k(T_i + T_e)/m_i v_m \) is the ambipolar diffusion coefficient and \( H_p \) the plasma scale height
  \[ k(T_i + T_e)/m_i g \]

- Vertical transport velocity becomes
  \[ u_{pl} = -\left( n_e m_i v_m \right)^{-1} \left[ \frac{dp_T}{dh} + n_e m_i g \right] \]
The Earth’s Ionosphere

• For historical reasons, the ionospheric layers are called D, E, F
  • D layer, produced by x-ray photons, cosmic rays
  • E layer, near 110 km, produced by UV and solar x-rays
  • F_1 layer, near 170 km, produced by EUV
  • F_2 layer, transport important
Ion composition

- $O^+$ dominates around F region peak and $H^+$ starts to increase rapidly above 300 km.
- $NO^+$ and $O_2^+$ are the dominant ions in E and upper D regions (Ion chemistry: e.g. $N_2^+ + O \rightarrow NO^+ + N$).
- D-region (not shown) contains positive and negative ions (e.g. $O_2^-$) and ion clusters (e.g. $H^+(H_2O)_n$, $(NO)^+(H_2O)_n$).

Figure: Daytime solar minimum ion profiles.
Ionospheric regions

Ionospheric regions and typical daytime electron densities:

- **D region**: 60–90 km,
  \[ n_e = 10^8–10^{10} \text{ m}^{-3} \]
- **E region**: 90–150 km,
  \[ n_e = 10^{10}–10^{11} \text{ m}^{-3} \]
- **F region**: 150–1000 km,
  \[ n_e = 10^{11}–10^{12} \text{ m}^{-3} \]

Ionosphere has great variability:

- **Solar cycle** variations (in specific upper F region)
- **Day-night** variation in lower F, E and D regions
- **Space weather** effects based on short-term solar variability (lower F, E and D regions)

**Figure**: Typical ionospheric electron density profiles.
Why do we care about conductivities?

Ionosphere is a plasma with an embedded magnetic field.

\[ \nabla \cdot [\sigma \cdot (E(r,t) + U(r,t) \times B)] = 0 \]

“The resulting electric field is as rich and complex as the driving wind field and the conductivity pattern that produce it”, Kelley, Ch. 3
Equations of Motion

Parallel equation of motion

\[ q E = m_i v_{in} u_i \quad -eE = m_e v_{en} u_e \]

Perpendicular equation of motion

\[ q \left( E_\perp + u_i \times B \right) = m_i v_{in} u_{\perp i} \]
\[ -e \left( E_\perp + u_e \times B \right) = m_e v_{en} u_{\perp e} \]
Collision Frequencies

Ion and electrons collide with neutrals as they gyrate. How they move in response to electric fields depends very much on the collision frequency relative to the gyro-frequency.
Conductivity

- **Pedersen conductivity (along $E_\perp$) perpendicular B, parallel E; horizontal**

- **Hall conductivity (along $E \times B$)**

- **Parallel conductivity**

- **Conductivity tensor**
Ionosphere at high, middle and low latitudes

- **High-latitude ionosphere** (polar cap, cusp, auroral oval): intense electric fields mapping from the magnetosphere, particle precipitation, effects of magnetospheric substorms.

- **Mid-latitude ionosphere**: occasionally high-latitude electric fields may penetrate to mid-latitudes, effects of magnetic storms.

- **Low-latitude ionosphere**: small electric fields, high day-time conductivities due to solar radiation (equatorial electrojet).

**Figure**: IMF coupling to the magnetosphere.
GPS TEC Map from 29-Oct-2003 20:00:00 to 29-Oct-2003 20:20:00

High Latitudes
Mid-Latitudes
Low Latitudes
Enhanced TEC Region observed in the Mid-Latitudes
Aurora observed over Venetie, Alaska
But how to explain these next two photographs? Answer in chat
Socorro New Mexico 20 Nov 2003

(from astronomy picture of the day)
West Texas 15 Sept 2000
near El Paso Texas

(from astronomy picture of the day)
The last few slides are to provide excitement about the ionosphere !!!
Solar Flare

A violent explosion in the Sun's atmosphere; energy equivalent of a hundred million hydrogen bombs. Giant bursts of X-rays and energy which travel at the speed of light

- Arrival: 8 min from Sun to Earth (149.6 million km)
- Duration: minutes to 3 hrs
- Daylight-side impact
Sept 6, 2017
This looping video shows a series of GOES-17 satellite images that caught an umbrella cloud generated by the underwater eruption of the Hunga Tonga-Hunga Ha’apai volcano on Jan. 15, 2022.

Crescent-shaped bow shock waves and numerous lighting strikes are also visible.
Initial waves had huge amplitudes and wavelengths (~2K km!)

Subsequent waves had 300-500 km wavelengths.
Summary

Ionospheric science continues to provide us with a wealth of new and exciting observations (e.g. the Steve phenomena)
It is a major contributor to space weather effects on radio wave propagation and on PNT systems (positioning, navigation, and timing).

“The resulting electric field is as rich and complex as the driving wind field and the conductivity pattern that produce it”, Kelley, Ch. 3