The Ionosphere and Thermosphere: a Geospace Perspective

John Foster, MIT Haystack Observatory

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Introduction – My Geospace Background
(Who is the Lecturer? Where is he coming from?)

• Member of the TEAM that developed the CEDAR concept & program in the 1980s

• Antarctica - Relativistic wave-particle interactions – M/I coupling

• Canada – International Satellite for Ionospheric Study (ISIS)

• Utah State Univ. - Alaska incoherent scatter radar studies of auroral disturbances and electrodynamics

• Yosemite conferences – broad topics in Geospace system science

• MIT - Radio-physics research investigating M-I-T phenomena from the ground and space

• Van Allen Probes - Ionospheric effects on magnetospheric processes & NL radiation belt acceleration

• I am data/observations oriented. I am NOT a modeler
MIT Haystack Observatory Complex
Westford, Massachusetts
Established 1956

Radio Astronomy
Atmospheric Science
Space Surveillance
Radio Science
Education and Public Outreach
Ionosphere: Balance of production and loss

**Production**: by Solar EUV at F region heights

**Loss**: Recombination and Ionospheric Chemistry

**Altitude Distribution**: Species dependent partial *pressure balance with gravity*

Diffusive Equilibrium or outflow (refilling) on depleted flux tubes

The Plasmasphere is an extension of the topside ionosphere

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International quiet solar year daytime ionospheric and atmospheric composition based on mass spectrometer measurements [Johnson, 1969; Luhmann, 1995].
The Coupled Geospace System

That region of space around Earth enveloped by its magnetic field
Geospace: The Inner Spheres

Earth - Biosphere, - Human Impact
Oceans
Neutral Atmosphere

Internal & External Effects
Ionosphere - chemistry & dynamics
- coupling above & below
- processes are interconnected
The Solar Cycle: F10.7 (27-Day Periodicity)

Solar Production

Red: 200-Day Moving Average

2007-2009 Extreme Solar Minimum

Sunspot Number

Year
TEC: Integrated vertical column density of through ionosphere and plasmasphere

Ionospheric Radar (ISR)

Plasmasphere is the high altitude extension of the ionosphere

Diffusive equilibrium determines quiet time profiles

Significant spatial structure results from M-I coupling
Solar wind flowing past Earth induces large scale circulation
To first order, cold plasma redistribution proceeds such that plasma parcels at ionospheric heights and at the apex of a magnetic field line move together in the E x B direction maintaining their magnetic field alignment.

[Foster, 1984]
Relationship of Convection and Precipitation

Empirical models of ionospheric electric field (Millstone Hill IS Radar) sorted by Evans’ auroral particle precipitation index (9 levels based on NOAA/Tiros data)

Equipotential contours of convection electric field are superimposed on patterns of precipitation energy flux. [Foster et al., 1986]
Joule Heating Rate $\Sigma P E^2$ is determined from individual observations of electric field and Pedersen conductivity over the lifetime of the AE-C satellite. [Foster et al, 1983]

The contribution of solar-produced dayside conductivity is important.

Joule energy deposition affects the dynamical properties of the thermosphere – winds, temperature, and composition.
Field-Aligned Currents Link the Magnetosphere and the Ionosphere

Joule dissipation of ionospheric currents is a major \( I - T \) energy source.
Quantitative patterns of field-aligned current density derived assuming that the total current is divergence free. Horizontal currents were derived from the empirical electric field models combined with conductances determined from precipitation particle energy flux and spectrum. [Foster et al., 1989]
Observations: GPS samples the ionosphere and plasmasphere to ~20,000 km. Dual-frequency Faraday Rotation Observations give TEC (Total Electron Content) of the ionosphere.

TEC is a measure of integrated density in a 1 m$^2$ column:

1 TEC unit = $10^{16}$ electrons m$^{-2}$
Storm Enhanced Density (SED)  5 min GPS TEC Snapshot

March 31, 2001  19:30 UT

SED Plume
Enhanced TEC

North America
Equatorial Ion Fountain

- Equatorial electrojet (E) and horizontal magnetic field (B) give upward $E \times B$ velocity.
- Gravity ($g$) pulls ions downward along $B$ to higher latitude.
- Off-equatorial peaks in ionospheric density result.

Figure 3 – Appleton Anomaly scheme.
Oct 30, 2003: CHAMP Buildup of TEC on the Dayside

Elevation angle > 40

13:00 Local Time

Vertical TEC Estimate (10^16 el/m^2)

Ground TEC

Spread EIA Crests

Magnetic Latitude (Dipole)

30 October, 2003

Global Coupled Effects
Redistribution Involves Significant Poleward Displacement of the EIA-Crest Plasma
Disturbed Ring Current drives Magnetic Field-Aligned Currents into the Sub-Auroral Ionosphere
Ionospheric Conductance is Low in the Trough

Latitude Variation of Ionospheric Density

$J \sim \sum E$

Ionospheric Trough

$R_H$

$R_I$

$E_P$

Mid-Latitude Ionosphere

Geodetic latitude

Auroral Ionosphere
The Plasmasphere Boundary Layer (PBL) at Ionospheric Altitudes

SAR (Stable Auroral Red) Arc

Observations made at Millstone Hill, Mass.
Ionospheric Structure Mirrors
Magnetosphere Processes and Dynamics,

GPS TEC mapped to equatorial plane
(correspondence with IMAGE EUV)

March 31, 2001

(e.g. Foster et al 2004)
Plasmaspheric drainage plumes: Mass-loading the magnetopause

Pushing back. From a perspective high over the North Pole of Earth, the cold plasma in the equatorial plane of Earth’s magnetosphere is sketched at two different times. **(A)** When solar-wind coupling is weak, the near-Earth reservoir (plasmasphere) is shown in green. **(B)** When coupling becomes stronger, the plume of sunward-convecting cold plasma eroding from the reservoir is seen. The cold plasma of the plume flows to the dayside boundary of the magnetosphere, where it interferes with the reconnection process. Space-based ultraviolet images of this cold-plasma movement can be seen in Goldstein (7).

Ionospheric plasma populates Earth’s plasmasphere

The plasmasphere drainage plume extends to the dayside magnetopause

[Borovsky, Science, 2014]
Space Weather Effects: Stormtime SED plumes develop steep TEC gradients along their edges, particularly at their poleward border where the SED overlaps the SAPS flow channel. Immediately poleward of the SED, collisional recombination in the high-speed SAPS flow reduces ion density and creates a deep ionospheric density trough and steepens the TEC gradient.
A Few Last Minute Facts about the Geospace Aspects of the Ionosphere

- Cold plasma of ionospheric origin populates Earth’s plasmasphere.
- Cold plasma circulation in the dayside magnetosphere maps to high latitude F region ionosphere dynamics.
- Ionospheric plasma structure, gradients, and dynamics are intimately related to geospace processes and have considerable space weather consequences.