UV Remote Sensing

Larry J. Paxton
Larry.paxton@jhuapl.edu
240 228 6871
We Seek an Understanding of the Atmosphere of the Earth and Other Planets

- UV remote sensing provides us an important technique for understanding, as well as testing our understanding of, the connections between the upper atmosphere and
  - The Sun
  - The magnetosphere
  - The ring current and plasmasphere
  - The lower atmosphere
- as well as the connections between the ionosphere and the thermosphere.
- TIMED is the first mission to make a systematic exploration of the coupled-ionosphere thermosphere system.
  - What is the state of the IT system?
  - What are the drivers and what is the response?
- In this talk I will focus on the Far Ultraviolet (115 to 180 nm) because we have instruments routinely making observations at these wavelengths.
- FUV data has quantitative as well as qualitative information.
To Understand the IT system We Have to Understand the Energy Balance

Temperature Change Rate = Energy Inputs - Energy Outputs + Energy Transport

Solar Heating  Radiation Cooling
Chemical Heating  Airglow Loss
Joule Heating  Heat Advection
Particle Heating  Adiabatic Heating
Wave Heating  Adiabatic Cooling

Aurora

Many of these processes have optical signatures.
The Earth in the FUV: The Subject of this Talk

First FUV image of the Earth—taken from the Moon by the Apollo 16 crew

Carruthers and Page, 1972
The processes that give rise to the emissions

- From laboratory studies and more than half a century of sounding rocket observations and almost a century of ground-based spectroscopy, we know the mechanisms that produce the signatures seen in the Earth’s optical spectrum.
- There are still many cross sections, processes, and reaction rates that are poorly known because they are difficult to measure in the lab.
The N\textsubscript{2} Lyman-Birge-Hopfield bands (a \(^1\Pi\) \textsubscript{g} – X \(^1\Sigma^+\)\textsubscript{g}) are an electric dipole forbidden transition but is allowed for magnetic dipole and electric quadrupole emission.

The upper state, a, is excited by photoelectron impact excitation.
Atomic Transitions Adequately Understood

The OI 135.6 $2p^4 \text{^3P} - 3s \text{^5S}$ is spin forbidden and produces a doublet. The OI 130.4 $2p^4 \text{^3P} - 3s \text{^3S}$ transition is allowed and produces a triplet.

Note the green line and the red line.

From Meier, 1991
Radiative Transfer Theory is the Key to a Quantitative Understanding of Optical Observations

$I$ is the spectral radiance (specific intensity) – photons cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ steradian$^{-1}$

\[
\frac{dI}{ds} = -\chi I + \varepsilon
\]

- Volume emissivity or number of photons cm$^{-3}$ s$^{-1}$ Hz$^{-1}$ steradian$^{-1}$ added to the beam
- Probability per cm at a given frequency of the photon being scattered out of the beam – the extinction coefficient
- Change in intensity along a path length
From the Radiative Transfer Equation we can Derive Beer’s Law

\[
\frac{dI}{ds} = -\chi I + \epsilon
\]

let \( \epsilon = 0 \) and ignore resonant scattering then

\[
I[r, \hat{n}, v] = I[\infty, \hat{n}, v] \exp[-\tau_a[\infty, r]]
\]

Where the absorption optical depth, \( t_a \) is given by

\[
\tau_a[r', r, v] = \int_{s[r']}^{s[r]} \sigma_a[v] n[r'] ds
\]
Point at Which the Vertical Optical Depth Equals 1

O₂ SR Continuum

O₂ SR Bands
Stellar Occultation Observation Illustrates the Principals of a Limb Observation, Absorption, Airglow, and Refraction.

Tangent altitude

Spectra of the star are shown in each panel. The observation was made at twilight which contributes some airglow to the background. The spectrum of the star is in the center of each panel.

Image of star in a coaligned telescope
Stellar Occultation

At the top of the atmosphere, FUV spectra are shown in SPIM1 and SPIM 2. Oxygen absorption is seen here.

Image of star in a coaligned telescope.

Ozone absorption seen in SPIM2 and 3.

At the top of the atmosphere.
FUV Spectrum shows $O_2$ Absorption -150 km
Stellar FUV is gone – only foreground airglow remains – 71 km

HI 121.6
OI 130.4
OI 135.6
MUV Airglow is gone and stellar spectrum is severely attenuated -48 km
Click on the image to view the movie
And Now for Something Completely Different....
The General Form of the Radiative Transfer Equation Includes Multiple Scattering

Formal solution of the RT equation

\[ I[r, \hat{n}, \nu] = I[\infty, \hat{n}, \nu] \exp[-\tau[\infty, r, \nu] - t_a[\infty, r]] + \int \varepsilon[r, \hat{n}, \nu] \exp[-\tau[r, \nu] - t_a[r, r'] ds \]

Solving the integral form of the emission rate

\[ I[\vec{r}, \hat{n}] = \frac{1}{4\pi} \int S[\tau'] F[\tau'] d\tau' \]

where

\[ S[\tau] = S_0[\tau] + \int \frac{d\Omega'}{4\pi} \int S[\tau'] G[\tau', \tau] d\tau' \]

\[ S_0 = \frac{4\pi \varepsilon_0[\vec{r}]}{\sigma_0 n[\vec{r}]} = \frac{g[\vec{r}]}{\sigma_0} \quad \text{for photoelectrons} \]

\[ S_0 = \frac{4\pi \varepsilon_s[\vec{r}]}{\sigma_0 n[\vec{r}]} = \pi \sqrt{\pi} \Delta v_D T(\tau_s) \quad \text{for solar resonant scattering} \]

See e.g. Meier, 1991; Paxton and Anderson, 1992
He II 30.4 nm line

About 50% of the energy deposited into ionization processes in the IT system

X-rays are highly variable but their energy is largely deposited below the point where either the F-region ionosphere is formed or where FUV photons can escape.
Photoelectron Flux Calculations Show the Dependence on the Neutral Atmosphere

\[
\begin{align*}
\frac{d\phi^+}{ds} &= \frac{-1}{\langle \cos \theta \rangle} \sum_k n_k \left[ \sigma^k_a + p_e^k \sigma^k_e \right] \phi^+ + \frac{1}{\langle \cos \theta \rangle} \sum_k n_k p_e^k \sigma^k_e \phi^- + \frac{q}{2} + \frac{q^+}{\langle \cos \theta \rangle} \\
- \frac{d\phi^-}{ds} &= \frac{-1}{\langle \cos \theta \rangle} \sum_k n_k \left[ \sigma^k_a + p_e^k \sigma^k_e \right] \phi^- + \frac{1}{\langle \cos \theta \rangle} \sum_k n_k p_e^k \sigma^k_e \phi^+ + \frac{q}{2} + \frac{q^-}{\langle \cos \theta \rangle}
\end{align*}
\]

Inelastic cross section

Elastic scattering cross section

Probability

Contribution from direct photoionization

Photoelectron production in the range to due to cascading from higher energy photoelectrons undergoing inelastic collisions

\[
\begin{align*}
\sigma^k_a &= \sum_j \sigma^k_{aj} \\

q^+(\varepsilon, s) &= \sum_k n_k \sum_j \{ p^{k}_{aj}(E) \sigma^k_{aj}(E \rightarrow \varepsilon) \phi^-(E, s) + \left[1 - p^{k}_{aj}(E) \right] \sigma^k_{aj}(E \rightarrow \varepsilon) \phi^+(E, s) \} \\

q^-(\varepsilon, s) &= \sum_k n_k \sum_j \{ p^{k}_{aj}(E) \sigma^k_{aj}(E \rightarrow \varepsilon) \phi^+(E, s) + \left[1 - p^{k}_{aj}(E) \right] \sigma^k_{aj}(E \rightarrow \varepsilon) \phi^-(E, s) \}
\end{align*}
\]

From Banks and Kockarts
The Location of the Peak in the Cross Sections for Emission Due to Electron Impact is Important

- With a peak near 15 eV and an ionization energy for the major thermospheric constituents of around 15 eV, a photon has to have an energy of at least about 30 eV to be able to create a photoelectron that has a significant probability of exciting these FUV emissions.
- A 30 eV photon has a wavelength of about 40 nm.
- How far do these photons penetrate into the atmosphere?
- If they create a photon, can that photon escape?
- Are there many photons at those wavelengths and how does the solar spectrum vary with time?
The atomic oxygen lines show self absorption effects

\[ \sigma_T = \int \sigma(v) dv = \frac{\pi e^2}{mc} f_{12} = \frac{h\nu_0}{4\pi} B_{12} \]

\[ \sigma_0 = \frac{\sigma_T}{\sqrt{\pi \Delta \nu_D}} \quad \text{Line center cross section} \]

The line center optical depth is about 1 for OI 135.6 emissions but 100,000 for OI 130.4 above the \( \tau=1 \) point in the pure absorber.

The emissions at 130.4 show the effect of multiple scattering.

From Meier, 1991
130.4 nm Images Show the Effect of Multiple Scattering

- Narrowest features are 25 km across.
- September 10, 2005 over the south pole near midnight MLT.
Fig. 6a. S-4 FUV dayglow spectrum (solid line) on 9 April, 1978 for nadir viewing from 205 km (Co et al., 1988). The spectrum is normalized to 1.0. The spectral resolution is 7 A. The dashed curve is the prediction of a Franck-Condon theoretical spectrum (R. Conway, private communication, 1988). No O H and O features in the S-4 data have been included in the theory. The excess emission seen in the S-4 N 1 data is the r

From Meier, 1991

FUV Spectrum of the Earth
The Ability to Model the Spectrum is a Key Enabler for Quantitative Studies

- The ability to model the spectrum, and account for all the processes that contribute to emission, are key to the ability to design instruments as well as to recover quantitative information.
- The modeling effort requires an understanding of the scattering properties of the atmosphere, chemistry and excitation process.
- RT models build on decades of laboratory work in the measurement of cross sections for photon and particle processes.
- There still are cross sections that need to be measured and processes that are poorly understood.
- Some of these can only be addressed by using the atmosphere as a natural laboratory.
  - Lifetimes of processes may dictate a chamber size that is impractical.
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The Ability to Model the Spectrum is a Key Enabler for Quantitative Studies
FUV Spectral Region Exhibits the Signatures of Space Weather in the Upper Atmosphere

- FUV spectral features were identified and interpreted during 30 years of rocket and spacecraft missions.

<table>
<thead>
<tr>
<th></th>
<th>HI (121.6 nm)</th>
<th>OI (130.4 nm)</th>
<th>OI (135.6 nm)</th>
<th>N₂ (LBHs)</th>
<th>N₂ (LBHL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dayside Limb</td>
<td>H profiles and escape rate¹</td>
<td>Amount of O₂ absorption¹</td>
<td>O altitude profile</td>
<td>Amount of O₂ as seen in absorption</td>
<td>N₂, Temperature</td>
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<td>Dayside Disk</td>
<td>Column H</td>
<td>Amount of O₂ absorption¹</td>
<td>Used with LBHs to form O/N₂</td>
<td>N₂, Solar EU</td>
<td>Solar EU</td>
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<tr>
<td>Nightside Limb</td>
<td>H profile and escape rate</td>
<td>Ion/ENA precipitation</td>
<td>EDP</td>
<td>Ion/ENA precipitation characteristic energy</td>
<td>Ion/ENA precipitation characteristic energy</td>
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<td>HmF2</td>
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<td>NmF2</td>
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<td>Nightside Disk</td>
<td>Geocorna and Ion/ENA precipitation</td>
<td>Ion/ENA precipitation</td>
<td>ñn₂ds (line of sight)</td>
<td>Ion/ENA precipitation</td>
<td>Ion/ENA precipitation</td>
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<td>ñnₐdz (vertical TEC)</td>
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<td>Ion/ENA precipitation</td>
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<tr>
<td>Auroral Zone</td>
<td>Region of proton precipitation</td>
<td>Auroral Boundary and amount of column O₂ present¹</td>
<td>Region of electron and (possibly) proton precipitation</td>
<td>Used with LBHI to form Eo and the ionization rate and conductance information</td>
<td>Measure of the effective precipitating flux, used with LBHI to form Eo and the ionization rate and conductance information</td>
</tr>
</tbody>
</table>
Remote Sensing is Indirect: How Do We Retrieve Information?

- Inverse techniques are relatively new in their application to IT problems.
- Both forward modeling and inverse processes use the same building blocks.
From Our Ability to Simulate the Scene and the End to End Performance We Can Design an Instrument

\[
\frac{C}{t} = A\Omega E \int 4\pi I(\lambda)\phi(\lambda)d\lambda
\]

Where

- \(C\) = counts
- \(t\) = integration period
- \(A\) = collecting area
- \(\Omega\) = field of view
- \(E\) = efficiency
- \(\phi(\lambda)\) = normalized spectral shape
- \(4\pi I\) = Intensity in Rayleighs

where 1 Rayleigh = 10^6 ph/cm^2/s into 4\pi steradians

Increasing \(A\) increases the mass (and cost) of the instrument
Increasing \(\Omega\) decreases the spectral resolution
Increasing \(t\) improves statistics (by the square root) but degrades resolution (linearly)
Increasing the bandpass improves statistics but can degrade the products
The Trade Space for the Optical Design is Constrained by Many Factors

\[
\frac{C}{t} = \int \frac{4\pi I(\lambda) \phi(\lambda) d\lambda}{4\pi} \left( \frac{h}{f} \right) \left( \frac{m}{d} \right) A_g T Q_e D_e
\]

Where
- \( h \) = slit height
- \( f \) = focal length
- \( m \) = grating order
- \( d \) = grating ruling density
- \( A_g \) = filled area of the grating
- \( T \) = transmission (product of all reflectivities)
- \( Q_e \) = quantum efficiency of the photocathode
- \( D_e \) = detector electronics efficiency

You need to make the slit (instantaneous FOV) as large as possible while keeping the focal length short. You’d like to operate with a coarsely ruled grating in high order with as large a grating as possible while minimizing reflections and still getting adequate imaging properties. A high \( Q_e \) is desirable but may lead to a shorter lifetime as may an amplification that leads to high counting efficiency.
In Both Forward Modeling and Inversions the Instrument Needs to be Well Characterized and Designed with a Measurement in Mind

What is the variability of the IT system?

What are the energy inputs into the IT?
Provide high latitude inputs
Provide global scale measurements of auroral emissions under all illumination conditions
Provide neutral density profiles in the thermosphere
Provide ionospheric information

Maximize the coverage from s/c altitudes
Handle contrast from day to night of 1000x in intensity
Provide disk sampling interval of 10km or better
Choose solar blind bands
Provide a photon counting detector with the dynamic range to handle day and night scenes
Provide limb sampling interval of 24km or better
Meet performance requirements during solar minimum and solar maximum
Enable pointing verification on-orbit
Enable on-orbit radiometric calibration

Spectrograph (SIS) Functions
1. cover 115 to 180 nm
2. Scan horizon to horizon
3. Scan on limb
4. Instrument throughput adjustable
5. Instrument resolution adjustable
6. Support two detectors
7. Compact design
8. Control spectral and spatial cross talk

SIS Detector Performance
1. Solar blind (λ > 200nm)
2. Spatial resolution
3. Responsivity
4. Adjustable gain to account for aging
5. Scrubbed plates to control gain changes
6. Dark count rate minimized

SIS Detector Electronics Performance
1. Solar blind (λ > 200nm)
2. Spatial resolution
3. Responsivity
4. Adjustable gain to account for aging
5. Scrubbed plates to control gain changes
6. Dark count rate minimized

SIS Scan Mechanism Performance
1. Lifetime requirement
2. Adjustable step size
3. Adjustable integration period
4. Uncertainty in pointing less than 3 km for limb measurements
5. Support stellar calibrations

Error Budget Maxima
1. Statistical measurement uncertainty < ±7%
2. Pointing error contribution < ±4%
3. Calibration errors < ±8%
4. Corrections and compression errors < 2%

coverage 115 to 180 nm
140 deg scan range in cross track direction
"fail-safe" slit mechanism
"pop-up" mirror to access either of two detectors
1.5 system
blazed holographic grating
CsI photocathode/Mg F window
Rowland circle design with toroidal grating
Detector HVPS covers range required from BOL to EOL
Precondition MCP
Use sealed tube design
Design electronics to be correctable to linear over entire required dynamic range
Dynamic range from 750 kHz to 0.1 Hz
Use wedge and strip anode
Design electronic for adjustable thresholding of valid events and include pulse shaping
Use flight heritage brushless DC motor design with encoders
Optimize AΩ for spatial resolution and lifetime
Ensure ability to detect at least one UV star/month to validate pointing
Ensure ability to detect at least one UV star/month to validate calibration
The Dayglow Spectrum of the Earth Drives the Specification of the Out of Band Response

The Factor of 1000 Contrast Between Day and Night Drives the Electronics and the Optics

- Drop in O₂ cross section
- Drop in O₃ cross section
- O₃ cross section maximum

Factor of 10,000 increase
GUVI/SSUSI Uses a Spectrographic Imager to Produce 3D Images

- GUVI/SSUSI scans across the disk and onto the limb
  - Column density information on the disk
  - Imagery for context and boundary location
  - Altitude profiles on the limb
Optical Design Maximizes End-to-End Throughput While Minimizing Package Size and Complexity
These Instruments are Small, for an Optical Instrument, Relatively Inexpensive

- Modern FUV instruments operate with photon counting electronics.
- An image intensifier converts incoming photons into a cloud of electrons that is localized on a position sensitive anode.
- That position is equivalent to knowledge of wavelength and spatial pixel.
**GUVI Produces Key Parameters that Provide Unique Insight into the IT**

<table>
<thead>
<tr>
<th>Dayside</th>
<th>Nightside</th>
<th>AURORAL Region</th>
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</thead>
<tbody>
<tr>
<td>O/N2</td>
<td>Electron Density Profile</td>
<td>Boundary</td>
</tr>
<tr>
<td>Qeuv</td>
<td>Bubble location and extent</td>
<td>Energy and flux</td>
</tr>
<tr>
<td>Neutral Density Profile</td>
<td>ENA precipitation</td>
<td>Imagery (day or night)</td>
</tr>
<tr>
<td>O+ above airglow profile</td>
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</tbody>
</table>

GUVI Image of the night-time ionosphere and ionospheric irregularities.

GUVI Image of the aurora over the US during the day in the middle of a large geomagnetic storm.
GUVI has a 7km (at nadir) spatial resolution

This is a series of individual scans in the 135.6 nm oxygen emission feature. The integration period for each pixel is 0.1 s.
The auroral algorithm uses the fact that O₂ absorption peaks at about 145 nm.

- The harder the spectrum (higher \(\langle E\rangle\)) the lower the ionization (and subsequent secondary electrons) peak will occur.
- The ratio of the N2 LBH bands where this absorption is important to the where it is negligible is a good indicator of the energy of the incoming particles from about 2 keV to 15 keV.
- Outside of that range the determination is less accurate.
- But it probably doesn’t matter for most applications.
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Proton Precipitation Can Also Be Important

- The proton energy and flux cannot be unambiguously determined from the measurement of HI 121.6.
- GUVI measures the total emission in the line.
- The protons can, however, be treated as being effectively electrons as determined by the ratio of LBHs/LBHI.
- This introduces a small error under the usual circumstances.

Note that for protons there is much less spread in the altitude of the peak in the ionization rate than for electrons.
E-region Quantities from GUVI “colors”

- LBHs/LBHI
- LBHI

\[ \langle E \rangle \]
\[ Q \]

\[ P = 1.8 \times 10^{10} \text{ ions cm}^{-2} \text{ s}^{-1} \]

- NmE
- HmE

\( \sigma \) and \( \Sigma \)

Where

\[ \Sigma_p = \frac{40 \langle E \rangle \sqrt{Q}}{16 + \langle E \rangle^2} \]

\[ \frac{\Sigma_H}{\Sigma_p} = 0.45 \langle E \rangle^{0.85} \]

Robinson et al., 1987 formulation is currently being used.
What Resolution Captures the Physics?
500km?
What is the Resolution Captures the Physics? 200km?
What is the Resolution Captures the Physics? 100km?
What is the Resolution Captures the Physics? 50km?
What is the Resolution Captures the Physics? 25km?
GUVI Detects Proton Precipitation

- We can begin to get an understanding of the spatial variability and scales of proton precipitation.
- Protons are not always a small contributor nor are they smooth.
The ionosphere responds to changes in the details in the solar flux and to changes in neutral composition and wind fields.

- How accurately can we predict the ionosphere on a global basis?
- UV remote sensing can provide us with a missing part of that picture.

Fig. 5.1. Typical midlatitude ionospheric electron density profiles for sunspot maximum and minimum conditions at daytime and nighttime. The different altitude regions in the ionosphere are labelled with appropriate nomenclature. (From Richmond, 1987.)
The Equatorial Ionosphere Shows the Global Coupling of the IT System

- Neutral winds in the low latitude E-region generate dynamo E-field as ions are dragged across B-field.
- Dynamo E-field is transmitted to F-region altitudes.
- Meridional neutral winds induce field-aligned plasma drifts at F-region altitudes.
- Corotational E-field causes the plasma to $E \times B$ drift to the east with the corotation speed.
Images of the Nightside Ionosphere Show Differences Between “Weather” and “Climate”

- A day of GUVI limb profiles compared to predictions from RIBG, an ionospheric climate model.
- The altitude axis runs horizontally and the plots are positioned at the equator-crossing point for an orbit.
- The climatological model embodies a different effective neutral wind and a different ExB drift than the observations.

From P. Straus
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- Both forward modeling and inverse processes use the same building blocks.

```
Measured Values
Measurement System
Transmission in the Medium
Source of the Signal
Physical Quantity
```

Forward Modeling → Inverse Problem
Discrete Inverse Theory Can Be Applied to the Nightside OI 135.6 nm Observations to Produce Electron Density Profiles

\[ B = W\eta ([\epsilon]) \]

Geometric weighting function

\[ \eta = \left( W_a^T C_{ma}^{-1} W \right)^{-1} W_a^T C_{ma}^{-1} \bar{B}_m \]

Covariance of the measurements

From the volume emission rate we can determine the O\(^+\) density (or electron number density if we assume \(n_e = n_{O^+}\))

\[ \eta = \alpha n_e n_{O^+} \approx \alpha n_e^2 \]

\[ \alpha = 7.3 \times 10^{-13} \text{ cm}^3 \text{ s}^{-1} \]

See DeMajistre et al, 2004;2005
A systematic comparison of GUVI data with hand-scaled data from ionosondes has been carried out.

The comparison indicates that GUVI can retrieve an accurate measure of NmF2.

Note that HmF2 is also a product of the GUVI retrievals as well as a TO+C (Total O+ Column).

The TOC product may be useful as a method of elucidating variations in the plasmasphere from TEC measurements.

A very important “discovery” is that some stations appear to show a systematic bias when compared to GUVI data.

DeMajistre, Paxton, and Bilitza, 2006.
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DeMajistre, Paxton, and Bilitza, 2006.
Retrievals Allow Us to Map Ionspheric Parameters on a Global Basis (at Fixed LST)

- GUVI NmF2 values for one day (2004/89) for a local solar time near midnight.
- The Equatorial Arcs are clearly visible.
- The important feature is that the parameters can be retrieved on a global basis and are not limited to locations of ground stations or subject to constraints of models as are the GPS TEC maps.
EDP Can Be Sliced in Different Ways

During the March-April 2004 CAWSES Campaign, there were a series of interesting events that arose due to a variety of solar and geomagnetic events. A slow CME (3/1) initiated a disturbance in geospace on 4/3/04.

Note general uplift, including uplift over Millstone Hill and SED over North America extending over Europe.
GUVI is Able to Map the Occurrence of Ionospheric Irregularities

Hendersen has done a study of the location, and magnitude of the crests in the EIA as well as bubble locations. Once a database has been produced we can begin to ask questions about mechanisms and our models for processes we have little direct information about such as what the underlying sources of the bubbles might be.

From Hendersen et al, 2004
Coordinated Studies With Ground and Space Assets Enhance our Knowledge

Fig. The ROCSAT passes across the magnetic equator did not show any evidence of the formation of the equatorial ionization trough. The background density between the depletions is $>10^5$ cm$^{-3}$. October 29, 2003

TIMED/GUVI detected depleted OI 135.6-nm emission at the locations of the plasma depletions. Elongation of the depletions along B-field lines and the simultaneous observations of the depletions at different altitudes support the association of the large depletions with smaller scale depletions or bubbles.
Inversion techniques can be applied to GUVI disk data to yield vertical structure. Inversion techniques can be applied to a number of problems including the use of disk observations to produce height information. These inversions and comparisons (Comberiate et al., 2005; 2006) have been demonstrated to be consistent with optical and radar observations.

Comparison of inversion of GUVI data with Julia radar images of EsF from Comberiate et al 2006
The Landscape of the Neutral Atmosphere

\[ \eta_{N_2} = \int_{z}^{\infty} [N_2] dz = 10^{17} \text{ cm}^{-2} \]

Fig. 30. Atmospheric composition from the MSIS-86 model at solar min (left curves) and max (right curves). The conditions chosen to represent min and max are given in Table VI. Temperature has been multiplied by $10^8$ to be on scale.
Tracing the Thermospheric Response Using the O/N$_2$ Ratio

- The ratio of 135.6 to LBH column emission rates has a close connection to ratio of corresponding column densities.
- GUVI uses 135.6/LBH ratio to obtain O to N$_2$ column density ratio (designated as O/N$_2$).
- O/N$_2$ changes as the depth of N$_2$ changes.
- The process is to pick an N$_2$ depth and examine the uniqueness of 135.6/LBH to O/N$_2$ at this depth.
- Strickland and Paxton (1992) first looked at this and found a strong correlation between calculated intensities and changes in thermospheric composition.
- Strickland, Evans, and Paxton (1995) have determined that the least spread in O/N$_2$ for a given value of 135.6/LBH occurs near an N$_2$ depth of $10^{17}$ cm$^{-2}$ (near 170 km). The standard deviation is less $\sim$ 1%.

Figure 9. O/N$_2$ versus 135.6/LBH at an N$_2$ reference depth of $10^{17}$ cm$^{-2}$ for the 324 unscaled TIGCM atmospheres. The results show that a nearly proportional relationship exists with uncertainty consistent with that shown in Figure 7b.
GUVI O/N$_2$ is well correlated with the negative phase of an ionospheric storm.
November Storm

GUVI O/N₂ Ratio

Nov 19, 2003
GUVI O/N₂ Ratio  Nov 21, 2003
GUVI O/N\textsubscript{2} Ratio  Nov 22, 2003
Storms Provide Useful Test Cases

The comparison of a dynamically driven quantity, such as O/N2, between observations and models allows us to test whether we have the onset and recovery phase of storms correctly modeled.

From Geoff Crowley’s initial comparison with TIMEGCM
Was there an Effect Due to the Asymmetric Inputs?

(a) GUV\(\text{O/N}_2\)

(b) 

[Graph showing magnetic field variations over time and space]
What Drives the Differences?

- Superstorms are particularly difficult to model and, more importantly, it is difficult to validate the model with observations.
- There are coupling pathways that tie the ions and neutrals.
- We are just beginning to explore these pathways by using coordinated data analysis.
GUVI Observations of Midlatitude O/N₂ may help us understand the Relative Roles of Composition and Dynamics in Determining TEC

- Now that we have a large database of O/N₂ and GPS TEC measurements for quiet and disturbed times, for all seasons and all local solar times we can do a simple comparison between TEC and O/N₂.
FUV remote sensing is a tool that has evolved over the last 35 years.

We have the tools and means in place to address the fundamental processes that shape the ionosphere-thermosphere system and connect the IT to the rest of geospace and the lower atmosphere.
What I would have liked to have told you about…

- The exciting work being done using GUVI and SuperDARN
- The use of UV imagery in AMIE
- Using two H Lyman $\alpha$ channels to determine the flux and energy of precipitating protons.
- Using all-reflection UV interferometers to determine velocities and outflow rates.
- How we might be able to determine the $O/N_2$ and $O_2/N_2$ in the aurora.
- How the OI 130.4 nm and 164.1 nm emission could be used to probe $O$ and $O_2$ in the lower thermosphere.
- More about the use of UV imagery to investigate the morphology of ionospheric bubbles and tides/waves in the ionosphere
- More about how we might be able to extract effective meridional winds and ExB drifts from nightside ionospheric imagery
- The use of multicolor limb retrievals to constrain, $O$, $O_2$, $N_2$, and $O^+$ on the dayside
- And more….
Where are the data?
Where are the data?

GUVI.jhuapl.edu
Data and Images are Available

- Level 1B data are calibrated and geolocated
- Level 2B are gridded
- Level 3 are higher level data products
  - Available as pictures or as numbers!
Data and Images are Available

GUVI Global Ultraviolet Imager

HOME
OVERVIEW
EXTENDED MISSION
USING GUVI DATA
GUVI DATA PRODUCTS
ACCESS GUVI DATA
DATA USAGE
DATA AVAILABILITY
SUMMARY IMAGES
PUBLICATIONS
EDUCATION

GUVI Data Products

LEVEL 1A Data Products
Spectrograph

LEVEL 1B Data Products (Current Version: version 8)
Imaging
Static Imaging

LEVEL 1C Data Products (Current Version: version 3)
Disk

LEVEL 2B Data Products
Day
Limb

LEVEL 3 Data Products
Aurora Data Products (E_b and Q)
Thermospheric O/N_2
Electron Density Profiles
O/N_2 and Total Electron Content (TEC)

Support Data Products
GUVI Housekeeping

GUVI O/N_2 Ratio
Sept 11, 2005

The Johns Hopkins University Applied Physics Laboratory
The Last Updated: October 21, 2005
Data and Images are Available

GUVI Global Ultraviolet Imager

GUVI Data Products

LEVEL 1A Data Products
- Spectrogram

LEVEL 1B Data Products (Current Version: version 8)
- Imaging
- Static Imaging

LEVEL 1C Data Products (Current Version: version 3)
- Disk

LEVEL 2B Data Products
- Day
- Limb

LEVEL 3 Data Products
- Aurora Data Products ($E_g$ and $Q$)
- Thermospheric $O/N_2$
- Electron Density Profiles
- $O/N_2$ and Total Electron Content (TEC)

Support Data Products
- GUVI Housekeeping

The Johns Hopkins University Applied Physics Laboratory
The Last Updated: October 21, 2005

GUVI O/N_2

Sept 13, 2005 0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4
Sept 11, 2005

CODE TEC

0 20 40 60 80
There are a number of references available that cover various aspects of UV/Vis phenomenology.

The seminal works are:


The basic reference for much of UV/Vis backgrounds phenomenology is still:


Auroral spectroscopy is discussed in


The most recent attempt at a comprehensive review of UV phenomenology is


Others include:

More of the forgotten lore…


A number of reviews covering the nightglow are available:


The Rayleigh is defined in
Radiative transport in planetary atmospheres is addressed at a basic level in many of the texts above. A number of techniques are discussed in:


Chandrasekhar and Ivanov are primarily concerned with analytic approaches to the problem. The standard references for UV work are:


The solution of the problem for a generalized spherical atmosphere is discussed in

Inversions


In the Case of Single Scattering Without Absorption the Equations are Very Simple

\[
\text{Ch}(\chi, \frac{r_0}{H}) = \frac{\int_{r_0}^{\infty} n(r)V(\chi, r)dr}{\int_{r_0}^{\infty} n(r)dr} = \frac{\eta(\chi, r_0)}{\eta(\chi=0, r_0)}
\]

\[
4\pi I(\chi, r_0) = g\text{Ch}(\chi, \frac{r_0}{H}) \int_{r_0}^{\infty} n(r)dr = g\text{Ch}(\chi, \frac{r_0}{H})n(\frac{r_0}{H})H
\]

\[
4\pi I(\chi=90^\circ, r_0) = g \left(\frac{2\pi r_0}{H}\right)^{-1/2}n(\frac{r_0}{H})H
\]