Modeled And Observed N2 Lyman-birge-hopfield Band Emissions Earth's Dayglow: A Comparison

Donald Murray  
*University of Central Florida*

Find similar works at: [https://stars.library.ucf.edu/etd](https://stars.library.ucf.edu/etd)

This Doctoral Dissertation (Open Access) is brought to you for free and open access by STARS. It has been accepted for inclusion in Electronic Theses and Dissertations, 2004-2019 by an authorized administrator of STARS. For more information, please contact STARS@ucf.edu.

**STARS Citation**

[https://stars.library.ucf.edu/etd/3274](https://stars.library.ucf.edu/etd/3274)
MODELED AND OBSERVED
N$_2$ LYMAN-BIRGE-HOPFIELD BAND EMISSIONS IN THE EARTH’S
DAYGLOW A COMPARISON

by

D. JAY MURRAY
B.S. University of Central Florida, 1998
M.S. University of Central Florida, 2000

A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
in the Department of Physics
in the College of Sciences
at the University of Central Florida
Orlando, Florida

Spring Term
2008

Major Professor:
Richard Eastes
ABSTRACT

Ultraviolet (UV) spectra obtained from Earth’s dayglow contain important information for understanding the thermosphere, and the N₂ Lyman-Birge-Hopfield (LBH) bands are possibly the most useful emission. To be useful, a thorough understanding of how the LBH band emission varies with altitude and latitude is essential to present and future use of this emission by space-based remote sensors. Excited by photoelectron impact on N₂ leading to transitions from the a \(^{1}\Pi_{g}\) state to the ground state, the LBH emissions radiate between 1270 and 2400 Å. In addition to being populated by electron impact excitation, the a \(^{1}\Pi_{g}\) state is populated by radiative and collisional cascading from adjacent singlet states a’ \(^{1}\Sigma_{u}^{-}\), and w \(^{1}\Delta_{u}\) (Eastes, 2000). Ultimately, the intensity is most dependent on low energy electron flux (Ajello and Shemansky, 1985; Meier, 1991) because that is where the electron impact scattering cross sections of the singlet states are the largest. This dissertation presents modeled LBH profiles produced using the Intrasystem Cascade Excitation (ICE) model (Eastes, 2000) with photoelectron fluxes calculated using the Continuous Slowing Down (CSD) model (Jasperse, 1976). Both of these models implement the Mass Spectrometer and Incoherent Scatter (MSIS) to model an atmosphere. Modeled emissions are compared against observations by the High resolution Ionospheric and Thermospheric Spectrograph (HITS) on the Advanced Research and Global Observation Satellite (ARGOS). This dissertation will investigate the LBH emissions in detail and ultimately use them for remote sensing of thermospheric temperatures.
I would like to thank my wife Lori and my two children Zac and Madison. This process takes time and attention away from all else including family. Thank you for your patience. My mentor and friend Richard Eastes introduced me to atmospheric science, gave me the opportunity to travel, and provided me with funding. I am forever in your debt. Lastly, my sincere thanks to both Arve Aksnes and Andre Krywonos who offered suggestions long after others would have lost patience.
# TABLE OF CONTENTS

LIST OF FIGURES vi

LIST OF TABLES x

LIST OF ACRONYMS/ABREVIATIONS xi

1. INTRODUCTION 1

2. ATMOSPHERIC EMISSIONS 10

   2.1. Airglow 17

      2.1.1. Nightglow 21

      2.1.2. Twilightglow 23

      2.1.3. Dayglow 24

   2.2. N\textsubscript{2} Lyman-Birge-Hopfield emissions 31

3. MODELING AND OBSERVATION OF LBH LIMB PROFILES: A COMPARISON 33

   3.1. Introduction 34

   3.2. Technique: Incorporating Model and Observation 37

      3.2.1. Observations from ARGOS/HITS 37

      3.2.2. Modeling the LBH Emissions 38

         3.2.2.1. Solar Irradiance 38

         3.2.2.2. O\textsubscript{2} Cross Section 41

         3.2.2.3. Cascade 41

   3.3. Results and Discussion 46

   3.4. Conclusion 57

4. REMOTE SENSING OF NEUTRAL TEMPERATURES 59

   4.1. Introduction 59
4.2. Inversion Technique

4.3. Comparison

4.4. Satellite drag data

4.5. Sources of observational error

4.6. Results

4.7. Conclusion

5. SUMMARY

APPENDIX: PROGRAMS

REFERENCES
LIST OF FIGURES

Figure 1-1. Visible radiation from the Sun passes through Earth’s atmosphere, as do some radio waves, microwaves, and infrared. Other wavelengths such as X-rays and ultraviolet radiation are absorbed (heating the upper atmosphere), or reflected back into space. (Image Tompson Higher Education)....................................................................................................................................... 2

Figure 1-2. The ionosphere allows radio waves to reflect and bounce back down to Earth past the horizon. Amateur radio operators utilize this behavior to communicate over great distances. This phenomenon is enhanced in the evening. As the source of the ions (the Sun) is removed, the weaker and more absorbent layer dissipates and there is stronger reflection of radio signals. (Image courtesy Thomson Higher Ed)............................................................................................ 4

Figure 1-3. Earth’s moon and airglow are visible above the horizon. The airglow is light that is emitted by the atmosphere, similar to the way a fluorescent light glows. The image above was captured using a digital still camera aboard the Space Shuttle Columbia. (Image courtesy NASA)......................................................................................................................................................... 5

Figure 1-4. The number of sunspots increases during periods of high solar activity. Sunspots can cause solar flares and solar flares can increase the amount of X-ray radiation emitted by orders of magnitude........................................................................................................................................ 7

Figure 1-5. The observations considered in this work are all from the 1440 to 1550 Å passband. In this wavelength range, photoabsorption is the result of the Schumann-Runge (SR) continuum of O₂. In fact the bulk of the analysis considered in this work is between 1460 and 1470 Å, the peak of SR continuum. At this wavelength a cross section of $1.5 \times 10^{-17}$ cm² is appropriate. ...... 9

Figure 2-1. The view above, taken from the Space Shuttle, illustrates the thinness of the layer of atmosphere which envelopes our planet. Though it may be thin, the atmosphere provides Earth’s inhabitants with oxygen, warmth, and protection from harmful solar radiation. (Image courtesy NASA) .......................................................................................................................................... 11

Figure 2-2. A layer of ozone gas protects Earth’s surface, and those on it, from the Sun’s damaging UV radiation. The gas functions as nature’s sunscreen. The concentration of ozone is expressed in two ways in the plot above. The concentration gives the number of ozone molecules in a specified volume relative to the number of total molecules in that volume in parts per million (PPM) for example 6 ozone molecules per million molecules. The relative number density gives only the number of ozone molecules per volume and is expressed above with no units just as a measure of variation with altitude. For example there are about twice as many ozone molecules in a fixed volume at 25 km than there were at 15 km................................................................... 12

Figure 2-3. Temperature vs. altitude structure of Earth’s atmosphere, including its outermost regions (exosphere), and designations of different regions of the atmosphere based on this variation....................................................................................................................................... 13

Figure 2-4. Primarily made up of plasma formed from photoionization, the ionosphere is important for communication. Longer wavelength signals can actually "bounce" off of the
ionosphere allowing them to travel farther distances, but shorter wavelength signals can scatter causing a loss of strength. (Image courtesy Elbate Engineering LTD) ......................................................... 14

Figure 2-5. Remotely sensed data can be in the form of spectra, or an image. If the two are combined, the spatial information is retained and several levels of spectra can be identified through color. The image of Hurricane Bertha (July 1996) above uses color to communicate temperature information. (Photo courtesy NOAA) ...................................................................... 18

Figure 2-6. The nightglow above La Palma Spain on a moonless night, taken with the faint-object spectrograph of the William Herschel Telescope in March 1991. The sodium 5893 Å emission is evident in the center (labeled 5890/6). The sodium emission is actually a doublet, emitting at 5890 and 5896 Å but more often referred to as the 5893 Å sodium emission. (Image courtesy of ING group)................................................................................................................. 19

Figure 2-7. A simulation of the Earth’s airglow, specifically atomic oxygen 1304 Å, as viewed from behind the Earth with the Sun in the background. The bright orange facing the Sun is the dayglow, while the darker color represents the nightglow and lower emission. The bright aurora around the top of the image is caused by charged particles spiraling along Earth’s magnetic field lines crashing into the atmosphere. (Image, courtesy Computational Physics Inc.)..................... 25

Figure 2-8. The SPICAM instrument on board Mars Express is a UV-infrared dual spectrometer dedicated primarily to the study of the atmosphere and ionosphere of Mars. Spectra obtained from SPICAM enabled the identification of the the γ and δ bands of nitric oxide NO (respectively, transitions A^2Σ^+-X^2Π and C^2 Π-X^2Π) in the Martian atmosphere. (Bertaux et al., 2005) ............................................................................................................................................. 27

Figure 2-9. The image above is a measure of the relative solar irradiance obtained by the Solar EUV Experiment (SEE) aboard the Thermospheric, Ionospheric, Mesospheric, Energetics and Dynamics (TIMED) spacecraft. It is significant because the solar data in this Figure can be correlated with the airglow data obtained simultaneously (Figure 2.11). (Image courtesy Johns Hopkins Applied Physics Lab) ..................................................................................................... 28

Figure 2-10. In order to accurately model airglow observations the solar irradiance throughout a range of wavelengths in a required parameter. The simultaneous observations made of the solar spectra by SEE (Figure 2.10) and the UV airglow spectra made by the Global UV Imager (directly above) provide concurrent data for inversion (Image courtesy Johns Hopkins Applied Physics Lab).................................................................................................................................. 29

Figure 2-11. The LBH emissions are excited by photoelectrons, and emit in transitions from the a^1Π_g state to the ground state. The figure above is a modeled emission spectra which illustrates the relative intensities of the bands..................................................................................................... 32

Figure 3-1. Modeled LBH brightness using solar flux values provided by different scaling (1, 2, and 3) of the Hinteregger algorithm and the Solomon et al. (2001) approach discussed in Section 3.1.0. The increased brightness resulting from the Solomon et al. scaling is the most striking feature. ............................................................................................................................................. 39

Figure 3-2. Same as Figure 3-1, but with the four altitude profiles of modeled LBH brightness scaled to common amplitude. The increased brightness at the lower altitudes is the result of a
greater relative high energy flux which penetrates more deeply into the lower atmosphere, creating more photoelectrons........................................................................................................................................................................ 40

Figure 3-3. Modeled LBH limb emission profiles calculated using O$_2$ photoabsorption cross sections of 10, 15, and 20 x $10^{-18}$ cm$^2$. As expected, where there is sufficient density, lower photoabsorption leads to higher emission. Results in the upper atmosphere remain relatively unaffected because low density makes absorption insignificant. ................................................. 42

Figure 3-4. Same as Figure 3-3 but with the three altitude profiles scaled to a common amplitude. When the emission profiles are scaled to a common maximum, the profile shape emerges. At higher absorbance you see more of the surface of the atmosphere and the brightest emissions, coming from $\sim$ 150 km have less effect. The lower absorbance profile registers the relative difference between the peak brightness at $\sim$150 km and off peak................................................ 43

Figure 3-5. Modeled LBH brightness using cascading (CSD+ICE - solid line) and direct excitation alone (CSD - dotted line). The brightness increases by a factor of about 1.5 when cascading between the singlet states is included........................................................................... 44

Figure 3-6. Same as Figure 3-5 but with the two altitude profiles scaled to a common amplitude. ....................................................................................................................................................... 45

Figure 3-7. The percent difference $\{[(CSD+ICE)-(CSD)] / (CSD+ICE)\}$ in LBH brightness at altitude when calculating the LBH brightness with (solid line) and without (dashed line) cascading. Note that the two altitude profiles have been scaled to a common amplitude. .......................... 47

Figure 3-8. Similar to Figure 3.7, but for variations in the O$_2$ photoabsorption cross section. The results are symmetrical increasing the cross section pushes the result the opposite direction than does decreasing the cross section, and by similar amounts. ................................................................. 48

Figure 3-9. Similar to Figure 3.8, but for variations in the solar spectrum model. The effects on the profile shape are of similar size at higher altitudes. At lower altitudes the shape difference seen in Figure 3.2 is apparent. Higher emissions at lower altitudes lead to the difference. .......... 49

Figure 3-10. Maximum differences (%) in LBH brightness when varying solar spectrum models (solid line), O$_2$ photoabsorption cross section (dashed line) and inclusion or exclusion of cascading (dashed and dotted line) ........................................................................................................................................ 51

Figure 3-11. The modeled LBH altitude profile resulting from MSIS, CSD, and ICE. The input parameters were F10.7, F10.7 81 day average, Ap, and date. Local time was set to noon and latitude was set to 35 degrees north. HITS limb scans were split into 23 tangent altitude bins between 96 and 419 km data were averaged for the observations recorded. The data shown are for 28 July 2001............................................................... 52

Figure 3-12. The same procedure as the previous plot. The date is 29 July 2001........................ 53

Figure 3-13. The same procedure as the previous plot. The date is 30 July 2001........................ 54

Figure 4-1. A global perspective such as the one shown can only come from remotely sensed satellite data. The LBH emissions, which are caused by photoelectrons, are prevalent in the southern hemisphere in this composite image formed by combining data from 15 orbits. (Image courtesy Johns Hopkins Applied Physics Lab)................................................................. 61
Figure 4-2. The ARGOS spacecraft in final preparation for launch atop its Delta II launch vehicle, at Vandenberg AFB, CA in January, 1999. Launched on 23 February 1999 ARGOS carried the High-resolution Ionospheric and Thermospheric Spectrograph (HITS), a very high resolution (>-.5 Å over a 500-1500 Å passband) Rowland circle spectrograph. (Image courtesy Naval Research Lab)................................................................................................................................. 62

Figure 4-3. Broadening of the (1-1) emission with increased rotational temperature enables remote sensing of rotational temperatures in the thermosphere. Aksnes (2006) found good agreement between neutral temperatures from models and rotational temperatures for the LBH emissions observed on three geomagnetically calm days in July 2001. Note that the fitting performed in this study only fits the (1-1) band up to 1470 Å (the vertical dotted and dashed line) due to the proximity of the (5-4) band................................................................................................. 64

Figure 4-4. The Figure above illustrates the superposition of spectra used to produce a single, synthetic spectrum. Each of the spectra along the line of sight have a slightly different temperatures and consequently slightly different spectra. The greater the distance to the observation point, the greater the attenuation, and the less the contribution to the observed brightness. ..................................................................................................................................... 65

Figure 4-5. A typical spectrum in the 1440 – 1550 Å passband. The dashed line is the fitted background. The solid red line is the first pass model fit to the spectrum. The prominent bands are annotated with the vibrational states (initial-final). The LBH (1-1) band is the brightest LBH emission in the passband, and by fitting a superposition of spectra constructed using the ICE model the temperature is extracted. ..................................................................................................................................... 67

Figure 4-6. Neutral temperatures from 24 July 2001 obtained by inversion of high resolution satellite observations of N₂ LBH emissions (X), MSIS constrained by drag data (triangle), and MSIS (square). The dotted is counts = 300. All spectra with counts ≥ 600 = 600. Notice the two spectra with the lowest counts lie well outside the other data points illustrating the error associated with low counts............................................................................................................ 70

Figure 4-7. To retain some spatial information elliptical orbits are chosen. The figure above describes a satellite that reaches perigee at the equator. The apogee and perigee values for the different curves are listed in the legend (Marcos et al., 2006)........................................................................................................ 72

Figure 4-8. In the 1462-1470 Å wavelength range, a maximum count of less than 100 does not provide the signal to noise necessary to accurately determine broadening due to rotational temperature. .................................................................................................................................. 78

Figure 4-9. A higher maximum count reduces the relative uncertainty through the wavelength bins and allows the broadening due to rotational temperature to be more closely determined than the spectra in the previous Figure. ........................................................................................................... 79

Figure 4-10. In the image above the peak of the observed emissions should occur near 145 km, it is reported as ~ 100 km. To ensure uniformity in this study the altitude of peak emission in the 1440-1550 Å passband was adjusted to occur near 145 km. ....................................................................................................................... 81
LIST OF TABLES

Table 2-1. Four main airglow emissions, their wavelength, and the responsible element. .......... 20
Table 2-2. A brief history of the study of Earth’s airglow ............................................................. 30
Table 3-1. Chi-square values when comparing modeled and measured Lyman-Birge-Hopfield altitude profiles. ............................................................................................................................ 55
Table 3-2. A summary of best fit parameters from Table 1 .......................................................... 56
Table 4-1. Averaged (daily) modeled temperature profiles which best fit HITS data ............... 73
Table 4-2. Same as Table 1 but with smoothed spectra, (average every five spectra) ............... 74
Table 4-3. Number of Individual spectra from each technique which best fit HITS data ............ 75
Table 4-4. Smoothed spectra used to produce Table 1 ................................................................. 76
### LIST OF ACRONYMS/ABBREVIATIONS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARGOS</td>
<td>Advanced Research and Global Observation Satellite</td>
</tr>
<tr>
<td>CSD</td>
<td>Continuous Slowing Down</td>
</tr>
<tr>
<td>EUV</td>
<td>Extreme UltraViolet</td>
</tr>
<tr>
<td>GUVI</td>
<td>Global UltraViolet Imager</td>
</tr>
<tr>
<td>HITS</td>
<td>High resolution Ionosphere and Thermosphere Spectrograph</td>
</tr>
<tr>
<td>ICE</td>
<td>Intrasytem Cascade Excitation</td>
</tr>
<tr>
<td>LBH</td>
<td>Lyman-Birge Hopfield</td>
</tr>
<tr>
<td>LORAAS</td>
<td>LOw Resolution Airglow and Aurora Spectrograph</td>
</tr>
<tr>
<td>MSIS</td>
<td>Mass Spectrometer and Incoherent Scatter</td>
</tr>
<tr>
<td>SEE</td>
<td>Solar EUV Experiment</td>
</tr>
<tr>
<td>SNOE</td>
<td>Student Nitric Oxide Explorer</td>
</tr>
<tr>
<td>TIMED</td>
<td>Thermosphere Ionosphere Mesosphere Energetics and Dynamics</td>
</tr>
<tr>
<td>UV</td>
<td>UltraViolet</td>
</tr>
</tbody>
</table>
1. INTRODUCTION

When solar radiation encounters Earth’s atmosphere it may reflect back into space, it may be absorbed, or it may pass through the atmosphere and strike Earth’s surface (Figure 1.1). On clear days visible light passes through the atmosphere without much loss, as do radio waves, some microwaves, and infrared radiation.

While the visible wavelengths pass through the atmosphere, X-rays and most Ultraviolet (UV) radiation don’t make it down to the surface very readily, lucky for us, but are absorbed and heat the upper atmosphere. This higher energy radiation (the X-rays and UV) can also ionize and dissociate the upper atmosphere. This is called photoionization and photodissociation respectively, and both of these processes can result in dayglow emissions.

Photodissociation occurs when radiation breaks apart a molecule. For example, an oxygen molecule (O$_2$) can break into two oxygen atoms (O + O). When photodissociation products recombine they emit light. When this recombination occurs after the Sun has set, it produces nightglow.

Photoionization occurs when high energy photons (radiation) “knock electrons off” of the molecules and atoms. Electrons released in this way may then collide with other molecules and atoms, exciting then and enabling them to emit light. The photoionization that produces the electrons also produces the region of the atmosphere known as the ionosphere.

The ionosphere is a region in the upper atmosphere containing electrons, atoms and molecules as well as neutral atmosphere, and is sometimes described using three layers. The first ionospheric layer found was the so called E layer or region at about 110 km altitude.
Figure 1-1. Visible radiation from the Sun passes through Earth’s atmosphere, as do some radio waves, microwaves, and infrared. Other wavelengths such as X-rays and ultraviolet radiation are absorbed (heating the upper atmosphere), or reflected back into space. (Image Tompson Higher Education)
It is used by radio operators as a surface from which signals can be reflected to distant stations. Above the E layer, is the F layer which also reflects radio waves. The F layer consists of two parts F1 is at about 170 km, and F2 at about 250 km altitude. The lowermost region of the ionosphere, the D layer, is below 80 km or so and principally absorbs radio waves. The reflection of the E and F layers makes long distance radio communication possible for amateur radio enthusiasts. In the evening when the source of the ionization (the Sun) is removed, the lower level (the D level) of the ionosphere begins to disappear. This allows radio signals to reflect from higher altitudes, leading to greater ease of radio communication (Figure 1.2).

The layers described are not fixed in altitude but dynamic, and there is no line in the sky but a continuum of charged particle density. This change in density creates a barrier, and the more sharply the density changes (E and F layers) the greater the reflection. An analogy to this barrier is driving through the rain at night. If it is raining just a bit the light from the headlights passes into the rain and vanishes in the distance. If the density of the raindrops is much greater (if it’s raining very hard) the headlights reflect back, you can’t see far ahead.

Spectra emitted by the atmosphere during daylight hours (known as dayglow Figure 1.3) contains information about the atmosphere’s chemistry, and constituents, as well as the solar conditions which may drive the emissions. In the upper atmosphere, emissions in the UV are of particular interest to monitor the solar energy input into Earth’s atmosphere. Due to scattering and absorption of the UV, observation of these emissions is performed from above the dense lower atmosphere. Today there are satellites which view Earth’s airglow twenty four hours a day. The availability of satellite based observations, advancement of detector technology (precision optics, CCD counters, data transfer) produces a constant stream of data.
Figure 1-2. The ionosphere allows radio waves to reflect and bounce back down to Earth past the horizon. Amateur radio operators utilize this behavior to communicate over great distances. This phenomenon is enhanced in the evening. As the source of the ions (the Sun) is removed, the weaker and more absorbent layer dissipates and there is stronger reflection of radio signals. (Image courtesy Thomson Higher Ed)
Figure 1-3. Earth’s moon and airglow are visible above the horizon. The airglow is light that is emitted by the atmosphere, similar to the way a fluorescent light glows. The image above was captured using a digital still camera aboard the Space Shuttle Columbia. (Image courtesy NASA)
Variations in the solar irradiance affect the dynamic nature of Earth’s atmosphere. Different regions of the solar spectra experience variations of different magnitudes. The extreme ultraviolet (EUV) and X-ray region shows the greatest variability. Part of this variability is due to the Sun’s solar cycle, an activity cycle about 11 years long Figure (1.4). Solar cycle variations range from about a factor of two through most of the EUV, to variations of more than an order of magnitude in parts of the X-ray spectrum. Superposed on top of the solar cycle variations there is additional short term (~27 day) variability. These variations, and more importantly their causes, are important to this study because they are the force driving the dynamic nature of the upper atmosphere. Photoionization, photodissociation, and photoexcitation, power the processes in the upper atmosphere.

The amount of solar EUV available in the lower atmosphere for photoelectron production is determined by the absorption cross sections of atomic oxygen, N₂, and O₂. Higher absorption cross sections for the atmospheric constituents result in smaller depth of penetration of the radiation. In order to model an emission in the lower atmosphere, the solar flux at altitude must be determined even if it has already been measured extra-terrestrially (above the atmosphere). This requires a density profile, which must calculated using the cross sections. The process, the inversion or modeling, requires that all parameters (cross sections, densities, irradiance) be self consistent. Consequently, accurate laboratory measurements are necessary to accurately model a process once the important parameters have been identified. One emission resulting from the photoelectrons discussed is the Lyman-Birge-Hopfield (LBH) bands of N₂.
Figure 1-4. The number of sunspots increases during periods of high solar activity. Sunspots can cause solar flares and solar flares can increase the amount of X-ray radiation emitted by orders of magnitude.
The LBH bands have been the subject of study and discrepancy. Appearing in the UV between 1270 and 2400 Å, the LBH emissions are used to remotely sense atmospheric constituent ratios relative to N₂, and to help determine energy input into the atmosphere. Early explanations described the excitation mechanism for this emission as purely photoelectron impact excitation. Later studies showed that direct excitation was inconsistent with measured spectra. As pertinent cross sections became available (Cartwright, 1977; Ajello and Shemansky, 1985; Katayama, et al., 1996) Eastes (2000) presented a model which satisfactorily accounted for these discrepancies by including some possibly overlooked processes.

When modeling the LBH emission for comparison with satellite observations, atmospheric absorption along the line of sight must be included. The observations considered in this work are all from the 1440 to 1550 Å passband. In this wavelength range, the absorption considered is the result of the Schumann-Runge (SR) continuum of O₂ (Figure 1.5). In fact, the passband is located at the very peak of the SR continuum as indicated in Figure 1.5, and a photoabsorption cross section of $1.5 \times 10^{-17} \text{ cm}^2$ is appropriate.
Figure 1-5. The observations considered in this work are all from the 1440 to 1550 Å passband. In this wavelength range, photoabsorption is the result of the Schumann-Runge (SR) continuum of O$_2$. In fact the bulk of the analysis considered in this work is between 1460 and 1470 Å, the peak of SR continuum. At this wavelength a cross section of $1.5 \times 10^{-17}$ cm$^2$ is appropriate.
2. ATMOSPHERIC EMISSIONS

The Earth is shrouded in a thin layer of atmosphere (Figure 2.1) which interacts with electromagnetic radiation from both terrestrial and extraterrestrial sources. While the upper atmosphere shields us from harmful radiation, the lowest portion of the atmosphere, the troposphere, is the region of most direct importance to life on Earth. The troposphere contains most of the atmospheric mass, and is the focus of the field of atmospheric science known as meteorology.

The next highest layer of the atmosphere, the stratosphere, is important because it contains the ozone layer, which shields life on Earth from harmful ultraviolet (UV) light from the Sun (Figure 2.2). The stratosphere is a zone of increasing temperature with altitude, due to absorption of solar UV radiation by ozone, and is the highest region in the atmosphere in which aircraft normally fly.

Although they are well above Earth’s surface (>50 km), the mesosphere, thermosphere, and exosphere (Figure 2.3) still affect mankind indirectly. Above about 80 km is the region called the ionosphere, a layer of ionized (electrically charged) gas atoms and molecules produced by photoionization. The ionosphere is of practical importance because it makes possible long-distance radio communications (radio waves can bounce off the ionosphere thus traveling past the horizon and back down to Earth, (Figure 2.4). The upper regions of the atmosphere are also of practical importance because some satellites have orbits that pass through these regions, and
Figure 2-1. The view above, taken from the Space Shuttle, illustrates the thinness of the layer of atmosphere which envelopes our planet. Though it may be thin, the atmosphere provides Earth’s inhabitants with oxygen, warmth, and protection from harmful solar radiation. (Image courtesy NASA)
Figure 2-2. A layer of ozone gas protects Earth’s surface, and those on it, from the Sun’s damaging UV radiation. The gas functions as nature’s sunscreen. The concentration of ozone is expressed in two ways in the plot above. The concentration gives the number of ozone molecules in a specified volume relative to the number of total molecules in that volume in parts per million (PPM) for example 6 ozone molecules per million molecules. The relative number density gives only the number of ozone molecules per volume and is expressed above with no units just as a measure of variation with altitude. For example there are about twice as many ozone molecules in a fixed volume at 25 km than there were at 15 km.
Figure 2-3. Temperature vs. altitude structure of Earth’s atmosphere, including its outermost regions (exosphere), and designations of different regions of the atmosphere based on this variation.
Figure 2-4. Primarily made up of plasma formed from photoionization, the ionosphere is important for communication. Longer wavelength signals can actually "bounce" off of the ionosphere allowing them to travel farther distances, but shorter wavelength signals can scatter causing a loss of strength. (Image courtesy Elbate Engineering LTD)
though the density is very low compared to the lower atmosphere, there are enough atoms and molecules to slow down satellites and limit the length of time a satellite can stay in low-altitude orbit around Earth.

Earth’s atmosphere is affected by the Sun differently at high altitudes than in the lower atmosphere. In the troposphere, the main effect of the Sun is to heat the atmosphere, either directly or indirectly, by heating of Earth’s surface. At high altitudes, however, the atmosphere is affected by solar ultraviolet and x-ray radiation. This high-energy electromagnetic radiation both heats and affects the composition of the upper atmosphere. However, while the variation in the intensity of this high-energy radiation may be greater than an order of magnitude through a solar cycle the variation seen in visible light from the Sun is only a few percent.

The heating effects of the Sun on the neutral (non-ionized) constituents of the upper atmosphere affect the density profile of the atmosphere. When the atmosphere is heated, it expands, and the density at high altitudes increases. This increased density results in increased drag on satellites in low Earth orbit, which reduces the orbital lifetime of satellites, or requires them to use on-board rocket propulsion to maintain themselves at the proper altitudes. For example, the Skylab space station, launched by NASA in 1973, fell to Earth in 1979 because of unexpectedly high upper-atmospheric drag, which in turn was caused by high solar activity (above-normal production of ultraviolet and X-ray radiation and energetic charged particles). Consequently, determining and predicting atmospheric heating is important to those who operate satellites.

Methods that can be used to measure the composition, temperature, density, and electrical charge of the upper atmosphere can be classified into two categories: in-situ techniques, in which the instruments used to make the measurements are actually placed in the atmospheric region of
interest, and remote sensing techniques in which the instruments are located at a distance from the region of interest.

In-situ techniques carry instruments into the desired regions of the atmosphere to make direct measurements. Balloons, rockets, satellites, and aircraft are all examples of possible transportation vehicles for in-situ techniques. A mass spectrometer is an example of an instrument which could implement this sort of technique. Mass spectroscopy requires a physical sample to perform the measurement and one way to do this is to put the spectrometer on a vehicle and transport it to the sample.

Remote sensing instruments on the other hand, may be located away from the region under investigation and may be active or passive. In active remote sensing a signal is emitted toward the region of interest and the returned signal is studied. Passive techniques simply receive emissions from the region of interest.

The instrumentation used in passive remote sensing is very similar to that used in astronomy. Cameras or spectrographs are used to view the electromagnetic radiation, which is either emitted by the region of the atmosphere being studied, or emitted by a distant source (e.g. the Sun or a star), but affected (absorbed or scattered) by the region of the atmosphere being studied. Cameras give increased spatial resolution and lower spectral resolution. Consequently, cameras are usually chosen to contrast differences in emissions in adjacent regions, or when the two dimensional shape of the region is important. Spectrographs, on the other hand, have high spectral resolution and limited spatial resolution. Hyperspectral imaging combines the two resolutions and is used to capture the image at many different wavelengths. In this way the spatial information and the spectral information are acquired simultaneously (Figure 2.6).
The spectrum of an emission contains information about the chemistry of the atoms or molecules because the spectra quantify the emitted energy very precisely:

$$E = \frac{hc}{\lambda}$$

Eqn. 1

Emission lines represent transitions made by the atom or molecule from one state to another. For example, the sodium emission described by equations 5 and 6 (section 2.1) emits a photon of wavelength 5893 Å. This emission can be seen in spectra shown in Figure 2.7. Attempting to obtain and explain spectroscopic signatures emitted from the upper atmosphere is the challenge, and the atmospheric emissions themselves are known as airglow.

2.1. Airglow

Airglow is an emission of light by Earth’s atmosphere, other than aurora, and was first documented by Anders Ångström, after whom the reference length (1Å = 10⁻¹⁰ meters) is named. The processes which produce the emission differ at different times of the day, and the airglow are named accordingly: nightglow, twilightglow, and dayglow. Table 2.1 lists the four main airglow emissions and the responsible element.
Figure 2-5. Remotely sensed data can be in the form of spectra, or an image. If the two are combined, the spatial information is retained and several levels of spectra can be identified through color. The image of Hurricane Bertha (July 1996) above uses color to communicate temperature information. (Photo courtesy NOAA)
Figure 2-6. The nightglow above La Palma Spain on a moonless night, taken with the faint-object spectrograph of the William Herschel Telescope in March 1991. The sodium 5893 Å emission is evident in the center (labeled 5890/6). The sodium emission is actually a doublet, emitting at 5890 and 5896 Å but more often referred to as the 5893 Å sodium emission. (Image courtesy of ING group).
Table 2-1. Four main airglow emissions, their wavelength, and the responsible element.

<table>
<thead>
<tr>
<th>Origin</th>
<th>Transition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>O atom</td>
<td>^1S→^1D</td>
<td>Green oxygen line, permanent, bright, very bright in dayglow, transition forbidden</td>
</tr>
<tr>
<td></td>
<td>(557.7 nm)</td>
<td></td>
</tr>
<tr>
<td>O atom</td>
<td>^1D→^3P</td>
<td>Red oxygen line, permanent, less bright than 557.7 nm, transition forbidden, enhanced at twilight, very strong in dayglow,</td>
</tr>
<tr>
<td></td>
<td>(630.0 nm)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(636.3 nm)</td>
<td></td>
</tr>
<tr>
<td>Na atom</td>
<td>^2P→^2S</td>
<td>Sodium D-line, Permanent, strong, enhanced at twilight, very strong in dayglow</td>
</tr>
<tr>
<td></td>
<td>(589.3 nm)</td>
<td></td>
</tr>
<tr>
<td>OH radical</td>
<td>Various vibration &amp; rotational states → ground</td>
<td>Meinel bands, very strong in nightglow, twilight, and dayglow, appear in red and near infrared</td>
</tr>
</tbody>
</table>
2.1.1. Nightglow

On average nightglow is the least bright of the airglow emissions, but historically it was the first of the airglow emissions observed. Although the total irradiance of the nightglow emission is feeble, the relative brightness is significant. On a moonless night, away from artificial sources, nightglow constitutes about 40% of observed light. This is about the same amount of illumination experienced when standing 100 meters away from a candle. Without instrumentation (using only the naked eye), this feeble emission can only be detected in a very dark environment, which explains why the least bright of the airglow emissions was the first observed.

Recombination is one process that produces nightglow. Ions produced during the daylight hours recombine with electrons, producing photons. This is one path to the 5577 Å oxygen emission (Equation 2. and 3.).

\[
\begin{align*}
O_2^+ + e & \rightarrow O + O(^1S) \quad \text{Eqn. 2} \\
O(^1S) & \rightarrow O(^1D) + h\nu (5577 \text{ Å}) \quad \text{Eqn. 3}
\end{align*}
\]

Chemical reactions between atmospheric constituents can also produce light. The low density of reactants (atmospheric atoms and molecules) results in a slow and steady rate of reaction, resulting in a glow that continues throughout the night. This recombination chemistry is another path leading to the atomic oxygen emission at 5577 Å (Eqn 4 and 5). Atomic oxygen combines to form an oxygen molecule, the released energy excites a third oxygen atom, which deexcites to produce the 5577 Å emission.
O + O → O₂ + hv → O + hv → O(¹S)  Eqn. 4
O(¹S) → O(¹D) + hv (5577 Å) Eqn. 1  Eqn. 5

Photoelectrons still present from earlier irradiation may excite a species and cause emission. This cause of emission becomes less significant as the evening hours progress and fewer electrons are available.

Although nightglow was studied first, the low radiance makes spectroscopic studies difficult, requiring lengthy exposures. Lengthy exposures unfortunately average out the variations in dynamic processes and deplete spatial information. For this reason interferometric techniques are used to obtain spectral resolution.

Descriptions of nightglow chemistry must utilize processes other than solar radiation, which may lead to alternative paths for the same reaction. An example is the sodium 5893 Å line. The nightglow reaction is believed to be:

\[ \text{NaO} + \text{O} \rightarrow \text{Na}(^2\text{P}) + \text{O}_2 \]  Eqn. 6.
\[ \text{Na}(^2\text{P}) \rightarrow \text{Na}(^2\text{S}) + \text{hv} \]  Eqn. 7.
An alternative mechanism for this emission is available in the twilight and dayglow that involves absorption and reemission of solar photons (resonant scattering).

\[ \text{Na}(^2S) + h\nu \rightarrow \text{Na}(^2P) \quad \text{Eqn. 8.} \]
\[ \text{Na}(^2P) \rightarrow \text{Na}(^2S) + h\nu \quad \text{Eqn. 9.} \]

### 2.1.2. Twilightglow

During twilight the upper atmosphere is still illuminated by the Sun from below the horizon. Atoms and molecules absorb this radiation and solar driven processes like photoionization, photodissociation, photoexcitation, and resonant scattering occur. This results in twilightglow. The same emissions visible in the nightglow may be seen in twilightglow, but they may result from different processes. For example, the 5893 Å Na line is greatly enhanced at twilight (relative to nightglow). This is because resonance scattering from solar photons is contributing to the sodium emission, and these photons are not available in nightglow. The reaction is outlined below. Sodium in the doublet S is excited to the doublet P by photoabsorption, and then upon relaxing emits a photon.

\[ \text{Na}(^2S) + h\nu \rightarrow \text{Na}(^2P) \quad \text{Eqn. 10.} \]
\[ \text{Na}(^2P) \rightarrow \text{Na}(^2S) + h\nu \quad \text{Eqn. 11.} \]

This is an example of how spectroscopic measurements of the same emission, made at different times of day, result in different conclusions about the atmospheric chemistry responsible
2.1.3. Dayglow

Daylight atmospheric emissions (dayglow) are the brightest of the three mentioned. The solar driven processes mentioned in the preceding paragraph are brighter with increased solar irradiance, resulting in more airglow (Figure 2.8). Although brighter, dayglow was historically the last of the airglow emissions discovered and studied. The brightness is offset by the Rayleigh scattering of the sunlight which masks emissions from wavelengths able to penetrate to Earth’s surface. In addition, higher energy (UV and above) emissions are absorbed by the dense lower atmosphere before making it to the surface. These obstacles delayed the study of dayglow until either more advanced instrumentation was developed or until there was a way to study it from above the scattering and absorption of the dense lower atmosphere.

Rocket borne attempts to obtain airglow measurements began in the mid 1950’s (Bedinger et al., 1953; Berg, 1955), and initial results were mixed. Bedinger et al. (1953) reported $\sim 10^{14}$ photons cm$^{-2}$ s$^{-1}$ while Berg recorded no luminosity. Even as instrumentation matured and techniques improved, reliable rocket borne measurements could only glimpse a fixed location if using an in situ technique and remote sensing techniques could only view along a line of sight for a few minutes (rockets acquire about ten minutes worth of data).

By the 1970’s to 1980’s, higher resolution spectra from rocket and satellite based sensors established the chemistry responsible for dayglow emissions (Gentieu et al., 1979; Anderson et al., 1980). This inspired laboratory work to establish necessary cross sections and reaction rates to model the emissions. Conway (1982) created an early model of $N_2$ emissions in the dayglow between 1250 and 1400 Å. By the early 1990’s inversion techniques were becoming available to
Figure 2-7. A simulation of the Earth’s airglow, specifically atomic oxygen 1304 Å, as viewed from behind the Earth with the Sun in the background. The bright orange facing the Sun is the dayglow, while the darker color represents the nightglow and lower emission. The bright aurora around the top of the image is caused by charged particles spiraling along Earth’s magnetic field lines crashing into the atmosphere. (Image, courtesy Computational Physics Inc.)
transform dayglow spectra into parameters such as atmospheric temperature, density, and concentration of select atoms and molecules (Meier and Picone, 1994). These techniques are not unique to Earth’s atmosphere and have been used to measure atmospheric constituents on other planets (Figure 2.9) (Feldman et al., 1993). As spectral resolution (instrumentation) improves, additional parameters are incorporated into models, which in turn glean more information. A brief history of Earth’s dayglow is given in Table 2.2.

Today billions of dollars are committed by the United States for new satellites and instrumentation specifically to study the UV dayglow (and aurora). This investment is made in expectation that UV remote sensing will provide increasing accuracy in the measurements of Earth’s upper atmospheric temperature, constituent ratios, and chemistry. UV remote sensing missions utilized in this paper include the Student Nitric Oxide Explorer (SNOE), Advance Research and Global Observation Satellite (ARGOS), and the Thermospheric, Ionospheric, Mesospheric, Energetics and Dynamics (TIMED). TIMED is unique in that it simultaneously studies the UV dayglow, using the Global UltraViolet Imager (GUVI), and the solar UV emissions using the Solar EUV Experiment (SEE) (Figure 2.10, and 2.11). It is believed that the photoelectron excited FUV dayglow is the means for remote sensing N₂, O₂, atomic oxygen, and temperature in the thermosphere. This dissertation will focus on N₂, specifically the Lyman-Birge-Hopfield bands.
Figure 2-8. The SPICAM instrument on board Mars Express is a UV-infrared dual spectrometer dedicated primarily to the study of the atmosphere and ionosphere of Mars. Spectra obtained from SPICAM enabled the identification of the γ and δ bands of nitric oxide NO (respectively, transitions $A^2\Sigma^+ - X^2\Pi$ and $C^2\Pi - X^2\Pi$) in the Martian atmosphere. (Bertaux et al., 2005)
Figure 2-9. The image above is a measure of the relative solar irradiance obtained by the Solar EUV Experiment (SEE) aboard the Thermospheric, Ionospheric, Mesospheric, Energetics and Dynamics (TIMED) spacecraft. It is significant because the solar data in this Figure can be correlated with the airglow data obtained simultaneously (Figure 2.11). (Image courtesy Johns Hopkins Applied Physics Lab)
Figure 2-10. In order to accurately model airglow observations the solar irradiance throughout a range of wavelengths in a required parameter. The simultaneous observations made of the solar spectra by SEE (Figure 2.10) and the UV airglow spectra made by the Global UV Imager (directly above) provide concurrent data for inversion (Image courtesy Johns Hopkins Applied Physics Lab)
Table 2-2. A brief history of the study of Earth’s airglow

1868 Anders Angstrom discovers green line is present in the night sky even when no aurorae are present

1920's Robert John Strutt (4th Baron Rayleigh) begins investigations [Note: he is referred to as the "airglow Rayleigh"; his father John William Strutt (3rd Baron Rayleigh) is the "scattering Rayleigh"]

1923 John McLennon & G.M. Shrum identify green line to be due to atomic oxygen

1929 Vesto Melvin Slipher discovers sodium layer (a contribution to airglow)

1931 Sydney Chapman suggests airglow is result of chemical recombination

1939 Chapman suggests reaction cycle to sustain sodium nightglow

1950 term "airglow" coined after other atmospheric emissions are identified

1960's Rocket borne studies of the visible dayglow spectra show continuum in the violet

1970 Barth and Schaffner study rocket observations of UV dayglow

Today the UV dayglow emissions are agreed upon as primary benchmark to characterize space weather
2.2. \textbf{N}_2 \text{ Lyman-Birge-Hopfield emissions}

\textit{N}_2 \text{ LBH emissions occurring in the dayglow radiate in the UV between 1270 and 2400 Å Figure (2.12). Excitation is driven by photoelectrons, and emitted by transitions from the a $^1\Pi_g$ state to the ground state. In addition to direct excitation, the a $^1\Pi_g$ state is populated by radiative and collisional cascading from adjacent singlet states (Eastes, 2000). Ultimately the intensity is dependent on low energy electron flux (Ajello and Shemansky, 1985; Meier, 1991). This dissertation will investigate the LBH emissions in great detail in the following chapters, and ultimately used them for remote sensing of thermospheric temperature profiles.}
Figure 2-11. The LBH emissions are excited by photoelectrons, and emit in transitions from the a $^1 \Pi_g$ state to the ground state. The figure above is a modeled emission spectra which illustrates the relative intensities of the bands.
3. MODELING AND OBSERVATION OF LBH LIMB PROFILES: A COMPARISON

A thorough understanding of how the N\textsubscript{2} LBH band emissions vary with altitude is essential to present and future use of these emissions for space-based remote sensing. In this chapter altitude profiles of modeled and observed LBH emissions are compared. Observations were measured by the High resolution Ionospheric and Thermospheric Spectrograph (HITS) aboard the Advanced Research and Global Observation Satellite (ARGOS). Besides comparisons with HITS data models are also used to examine the effects of solar irradiance, Intrasytem Cascade Excitation, and O\textsubscript{2} photoabsorption on the altitude profile of the LBH (1-1) emissions. Observations from altitudes of ~112-300 km were best matched when using solar spectra produced by scaling the Hinteregger formula as suggested by Solomon et al. (2001) (in 11 of 18 cases). In addition, inclusion of cascading between the singlet electronic N\textsubscript{2} states (a \textsuperscript{1}\Pi\textsubscript{g}, a’ \textsuperscript{1}\Sigma\textsubscript{u}, and w \textsuperscript{1}\Delta\textsubscript{u}) gives better agreement (34 of 36 cases) than direct excitation alone (2 of 36 cases). An O\textsubscript{2} photoabsorption cross section of 10 \times 10\textsuperscript{-18} cm\textsuperscript{2} yields the best agreement with observations (18 of 24 cases) in the 112–300 km altitude range. However, at the higher altitudes (~161-300 km), an O\textsubscript{2} photoabsorption cross section of 20 \times 10\textsuperscript{-18} cm\textsuperscript{2} yields the best match (21 of 24 cases). The larger O\textsubscript{2} photoabsorption cross sections derived for higher altitudes (and larger temperatures) are in agreement with previously reported temperature-dependent changes in the O\textsubscript{2} cross section. These results indicate models calculations give excellent agreement with observations when the appropriate values and processes are included, and the optimal values agree with recent experimental results for the physics involved. Therefore, current models provide the capabilities needed for space-based remote sensing.
3.1. **Introduction**

This chapter investigates the effect of three key parameters on modeled N$_2$ LBH emissions in Earth’s atmosphere. The O$_2$ photoabsorption cross section, cascading between the adjacent singlet states of N$_2$, and the wavelength distribution of the modeled solar irradiance are the parameters investigated. The results will be compared against observations obtained from HITS.

The Earth’s atmospheric composition and structure are of great importance for space weather predictions, and during the last three decades, ultraviolet (UV) remote sensing of the atmosphere has provided valuable insights into both. One of the emissions most frequently used in these studies is the N$_2$ Lyman-Birge-Hopfield band emissions (~1270 to 2400 Å), as they are bright, and produced by both auroral and dayglow phenomena. The N$_2$ LBH bands have been studied on several satellite missions, e.g. the Ultraviolet Imager (UVI) on Polar (Torr et al., 1995) and the Global Ultraviolet Imager (GUVI) on the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite (Christensen et al., 2003). Future missions also plan to observe the LBH bands, e.g. the proposed Global-scale Observations of the Limb and Disk (GOLD) instrument (Eastes et al., 2006) will monitor the these bands continuously from a geosynchronous orbit. To create reliable applications, an accurate understanding of the LBH band emissions is necessary. However, until recently excitation mechanisms for the LBH bands were not fully understood.

Earlier works that modeled LBH brightness from first principles airglow models, such as the Atmospheric Ultraviolet Radiance Integrated Code (AURIC) (Strickland et al., 1999) and the Continuous Slowing Down (CSD) model (Jasperse, 1976), assume direct excitation of the N$_2$
(a $^{1}\Pi_{g}$) state from the ground state. However, Cartwright et al. (1977) found that the adjacent singlet states (a’ $^{1}\Sigma_{u}$, and w $^{1}\Delta_{u}$) have comparable cross sections to the a $^{1}\Pi_{g}$ state. This prompted speculation that cascading between these two adjacent singlet states may contribute to the overall LBH emission. Further studies by Cartwright found the vibrational populations modeled using cascading between the single states were shifted toward the lower vibrational levels. Deviations from the vibrational distributions expected from direct excitation were later reported by Eastes et al. [1985], and Eastes and Sharp [1987].

Budzien et al. [1994] used measurements from the Ultra-Violet Limb Imaging experiment aboard Space Transport System number 39 (STS-39) to analyze LBH limb dayglow profiles above 200 km. Comparing their observations with model calculations of direct excitation, Budzien et al. [1994] observed significant differences in the distribution of the vibrational populations. In addition, Budzien et al. (1994) found the modeled brightness were too low by a factor of 1.4-1.6.

By including radiative and collisional cascading between the three lowest singlet states of N$_2$ (a $^{1}\Pi_{g}$, a’ $^{1}\Sigma_{u}$, and w $^{1}\Delta_{u}$), Eastes (2000) was able to provide good agreement between the relative distribution of modeled and observed vibrational populations. Further, Eastes (2000) showed that the inclusion of cascading increased the total emission from the LBH bands by a factor of ~1.6, consistent with the results of Budzien et al. (1994). This chapter investigates the effect of cascading on the altitude profile of modeled LBH emissions. In addition a comparison is made between observed LBH emissions, and models with and without cascade included.

Another factor influencing LBH emissions is the solar irradiance spectrum. The driving force behind space weather is the Sun. Hinteregger et al. [1981] developed reference solar spectra based on rocket measurements and obtained extreme ultraviolet (EUV) irradiances using
the Atmospheric Explorer (AE)-C and AE-E spectrometers. To quantify the solar soft X-rays and EUV irradiance on a particular day, numerous studies have adopted the Hinteregger et al. [1981] results. However, Solar EUV emissions vary by a factor of two over the solar cycle and some portions of the X-ray spectrum may vary by more than an order of magnitude [Solomon and Qian, 2005]. Results from the Student Nitric Oxide Explorer (SNOE) between mid 1998 and mid 1999 indicate the Hinteregger formulation significantly underestimates the emissions in the 2-20 nm region [Solomon et al., 2001]. To better model solar emissions, Solomon et al. [2001] suggest scaling factors of 6, 4, and 5 respectively for the 2-7 nm, 6-19 nm, and 17-20 nm Solar irradiances calculated using Hinteregger’s formula.

The observed brightness of the N$_2$ LBH band in the atmosphere also depends on O$_2$ photoabsorption. The O$_2$ Schumann-Runge (S-R) continuum occurs in the same wavelength range as the N$_2$ LBH bands. Several measurements of O$_2$ photoabsorption cross section within the S-R continuum have been reported in the last ~50 years, and they indicate there is significant temperature dependence. In studies at room temperature, Watanabe et al. [1953] determined the shape and symmetry of the O$_2$ cross section. At 1464 Å, the wavelength of the (1,1) [upper, lower vibrational state] to be examined later in this paper, Watanabe et al. [1953] reported a photoabsorption cross section of ~18 x 10$^{-18}$ cm$^2$. Later measurements by Ogawa and Ogawa [1465 Å). In a more recent study at higher temperatures (293-576 K), Kanik et al. [1997] [1975] yielded a cross section value of 14.5 x 10$^{-18}$ cm$^2$ (linear interpolation between 1460 and measured values between ~12.2 and ~13.0 x 10$^{-18}$ cm$^2$ for O$_2$ cross sections at 1492.63 and 1494.68 Å respectively. Yoshino et al. [2005] performed a similar temperature-dependent study for temperatures between 78-295 K and found the O$_2$ cross section at 1481.5 Å varies between
10.2 and $12.5 \times 10^{-18}$ cm$^2$ respectively. The common result in these studies is that the O$_2$ cross section increases with temperature.

To understand the physics in the upper atmosphere, many studies rely on N$_2$ LBH measurements. However, as described above, the LBH emissions depend on the solar spectrum, the O$_2$ photoabsorption cross section, and cascading between the singlet electronic N$_2$ states. The purpose of this study is to investigate the effects of these parameters on the LBH emission profile. This is accomplished through comparisons of model calculations and observations by the High resolution Ionospheric and Thermospheric Spectrograph (HITS) aboard the Advanced Research and Global Observation Satellite (ARGOS).

3.2. Technique: Incorporating Model and Observation

In this study, two separate comparisons are performed: (i) observations from ARGOS/HITS are compared with modeled LBH altitude profiles, and (ii) altitude profiles of LBH brightness are calculated for various values of the solar irradiance spectrum, O$_2$ photoabsorption cross section and cascade excitation, to study how each parameter affects the profile shape.

3.2.1. Observations from ARGOS/HITS

The ARGOS satellite was launched on 23 February 1999 into a sun-synchronous orbit at an altitude of 840 km. It began operations on 15 May 1999. HITS observed in 110 Å passbands between 500 and 1800 Å with a spectral resolution of $\sim 1.3$ Å full-width-at-half-maximum (FWHM) [Dymond et al, 1999]. The observations used in this study were obtained while HITS scanned the limb. While this passband includes emissions from all vibrational levels, the (1,1)
band at 1464 Å is the brightest and gives the largest signal to noise ratio of any single band. In this study, the relative brightness is determined using the (1,1) emission.

To analyze the (1,1) band, a nonlinear least squares approach is used to fit synthetic spectra to those observed. This fitting uses discrete inverse theory (DIT) [Menke, 1989] to find the rotational temperature, relative vibrational population, contribution by the (1-1) emission, background, 1493 Å atomic nitrogen contribution and O2 photoabsorption, that produce the best fit to the observed spectra. A Levenberg-Marquardt [Marquardt, 1963] scheme is used to adjust the parameters and minimize chi-square values. For more details, see Aksnes et al. [2006, 2007].

3.2.2. Modeling the LBH Emissions

3.2.2.1. Solar Irradiance

Four different solar irradiance models are used for calculating the LBH emissions. Three of the four models use Hinteregger’s algorithm with irradiances at energies greater than 88 eV scaled by 1, 2, or 3. The fourth model uses Solomon et al. [2001] scaling factors for Hinteregger’s algorithm. From analyses of SNOE data, Solomon et al. [2001] derived scaling factors of 6, 4, and 5 respectively for the 2-7 nm, 6-19 nm, and 17-20 nm wavelength ranges. Using these four solar models, and the solar conditions (F10.7 81 day average, F10.7, and Ap) for each day of observation, LBH emissions are calculated. Figures 3.1, and 3.2 illustrate the effect of solar irradiance spectra on modeled emissions. Observational solar conditions were retrieved from the Space Physics Interactive Data Resource (SPIDR).
Figure 3-1. Modeled LBH brightness using solar flux values provided by different scaling (1, 2, and 3) of the Hinteregger algorithm and the Solomon et al. (2001) approach discussed in Section 3.1.0. The increased brightness resulting from the Solomon et al. scaling is the most striking feature.
Figure 3-2. Same as Figure 3-1, but with the four altitude profiles of modeled LBH brightness scaled to common amplitude. The increased brightness at the lower altitudes is the result of a greater relative high energy flux which penetrates more deeply into the lower atmosphere, creating more photoelectrons.
3.2.2.2. O₂ Cross Section

The modeled brightness at any tangent altitude is a product of the volume emission rate, attenuated by O₂ photoabsorption, integrated through the line of sight. Using O₂ photoabsorption cross sections of 10, 15, and 20 x 10⁻¹⁸ cm² altitude profiles are assembled from the modeled emissions (Figure 3.3). Differences between the resulting profile and the benchmark profile are calculated after the profiles are scaled to unity and aligned (Figure 3.4).

Using recorded conditions for the dates studied (July 28-30 2001), the Mass Spectrometer and Incoherent Scatter (MSIS) – 86 model returned temperatures ranging from ~170 K at 112 km to ~1100 K at 300 km. In this large temperature range, ~930 K, the temperature-dependence of the O₂ cross section, discussed in Section 1, should have a significant effect on the LBH brightness profiles.

3.2.2.3. Cascade

Altitude profiles of the LBH emissions are modeled with and without cascading between the singlet electronic N₂ states. The former has been performed by using the Intrasystem Cascade Excitation model (ICE) [Eastes and Dentamaro, 1996], to augment the CSD model [Jasperse, 1976]. In Figure 3.5, modeled emissions are calculated using CSD only (dotted line) and CSD+ICE (solid line). Cascading increases the emission by a factor of about 1.5. When scaled to the same emission rate (Figure 3.6), the greatest difference in the two profiles (CSD versus CSD+ICE) occurs at the highest altitudes, reaching over 6% at 300 km. Above 250 km altitude, cascading makes a greater difference than the other two parameters.
Figure 3-3. Modeled LBH limb emission profiles calculated using O$_2$ photoabsorption cross sections of 10, 15, and 20 \times 10^{-18} \text{ cm}^2. As expected, where there is sufficient density, lower photoabsorption leads to higher emission. Results in the upper atmosphere remain relatively unaffected because low density makes absorption insignificant.
Figure 3-4. Same as Figure 3-3 but with the three altitude profiles scaled to a common amplitude. When the emission profiles are scaled to a common maximum, the profile shape emerges. At higher absorbance you see more of the surface of the atmosphere and the brightest emissions, coming from ~150 km have less effect. The lower absorbance profile registers the relative difference between the peak brightness at ~150 km and off peak.
Figure 3-5. Modeled LBH brightness using cascading (CSD+ICE - solid line) and direct excitation alone (CSD - dotted line). The brightness increases by a factor of about 1.5 when cascading between the singlet states is included.
Figure 3-6. Same as Figure 3-5 but with the two altitude profiles scaled to a common amplitude.
3.3. Results and Discussion

The effect of varying the model parameters is illustrated in Figures 3.7 through 3.8. The default values, against which the comparisons are made, are cascading “on” (CSD+ICE), an O\textsubscript{2} cross section of $15 \times 10^{-18} \text{ cm}^2$, and a solar spectrum based on the Hinteregger formula (scaling=1).

Considering direct excitation only (excluding ICE) changes the profile below 250 km by less than 2% (Figure 3.7). Between 250 and 300 km the difference increases continuously, reaching ~6% at 300 km. This difference at the higher altitudes is greater than the difference seen in either of the other two parameters.

Figure 3.8 presents the differences in the LBH brightness when changing the photoabsorption cross section by ±33% from the default value of $15 \times 10^{-18} \text{ cm}^2$. The greatest differences are found at altitudes below the emission peak. The differences increase with decreasing altitude, reaching -11% (8%) for a cross section of 10 (20) $\times 10^{-18} \text{ cm}^2$.

Four solar irradiance scalings were considered, scaling the Hinteregger algorithm by two or three at energies above 88 eV (Figure 3.9) results in differences in the modeled LBH brightness of less than 2%. Larger differences are seen below 140 km when using the Solomon et al. [2001] scaling factors, and at 100 km the differences reach ~8%.

Figure 3.10 illustrates the magnitude of the maximum differences made by each of the three parameters that were varied. At altitudes below the emission peak, the O\textsubscript{2} cross section and the solar irradiance modeled (see Figures 3.8 and 3.9) make the greatest difference (~ ten times

46
Figure 3-7. The percent difference \( \frac{[(CSD+ICE)-(CSD)]}{(CSD+ICE)} \) in LBH brightness at altitude when calculating the LBH brightness with (solid line) and without (dashed line) cascading. Note that the two altitude profiles have been scaled to a common amplitude.
Figure 3-8. Similar to Figure 3.7, but for variations in the O$_2$ photoabsorption cross section. The results are symmetrical: increasing the cross section pushes the result the opposite direction than does decreasing the cross section, and by similar amounts.
Figure 3-9. Similar to Figure 3.8, but for variations in the solar spectrum model. The effects on the profile shape are of similar size at higher altitudes. At lower altitudes the shape difference seen in Figure 3.2 is apparent. Higher emissions at lower altitudes lead to the difference.
the cascade difference). At 300 km however, inclusion or exclusion of cascading results in about three times the difference seen when varying the O₂ cross section, and about six times the difference seen when varying the solar model.

Modeled (solid line) and measured (asterisks) LBH emissions for 28, 29, and 30 July 2001 are shown in Figure 3.11, 3.12, and 3.13. This fit is illustrates the relative difference seen between the models and observations. The modeled emission includes cascading, the Hinteregger et al. (1981) algorithm with scaling=1, and an O₂ photoabsorption cross section value of 15 x 10⁻¹⁸ cm².

For each day of observation (28-30 July 2001), Table 1 lists the chi-squared values obtained when fitting with each permutation of the three model parameters to each of the three days considered. Table 2 is a summary of the chi-square results from Table 1. Cascading yields the best fit to the HITS observations in 34 of the 36 full profile cases.

The lowest O₂ photoabsorption cross section (10 x 10⁻¹⁸ cm²) results in chi-square minima for 18 of the 24 full profile (~112-300 km) cases. The highest O₂ photoabsorption cross section (20 x 10⁻¹⁸ cm²) gives chi-square minima for 21 of the 24 Topside Profile (~161-300 km) cases. These results suggest that the O₂ photoabsorption cross section increases as the altitude increases. This may be due to the temperature variation in the cross section cited earlier (Kanik et al., 1997; Yoshino et al., 2005). MSIS 86 returned temperatures ranging from ~700 K at 150 km, to 1100 K at 300 km. Using Yoshino et al. (2005) data for 1432.6 Å, which reports cross sections of 13.5 x 10⁻¹⁸ cm² and 14.2 x 10⁻¹⁸ cm² at 90 and 295 K respectively, a linear extrapolation gives a value near 17 x 10⁻¹⁸ cm² at 1000 K.
Figure 3-10. Maximum differences (%) in LBH brightness when varying solar spectrum models (solid line), O₂ photoabsorption cross section (dashed line) and inclusion or exclusion of cascading (dashed and dotted line)
Figure 3-11. The modeled LBH altitude profile resulting from MSIS, CSD, and ICE. The input parameters were F10.7, F10.7 81 day average, Ap, and date. Local time was set to noon and latitude was set to 35 degrees north. HITS limb scans were split into 23 tangent altitude bins between 96 and 419 km data were averaged for the observations recorded. The data shown are for 28 July 2001.
Figure 3-12. The same procedure as the previous plot. The date is 29 July 2001.
Figure 3-13. The same procedure as the previous plot. The date is 30 July 2001.
Table 3-1. Chi-square values when comparing modeled and measured Lyman-Birge-Hopfield altitude profiles.

<table>
<thead>
<tr>
<th>Solar model used</th>
<th>( O_2 ) cross section ( \times 10^{18} ) cm(^2)</th>
<th>w/ &amp; w/o ICE</th>
<th>28-Jul-01 Full Profile 112-301 km</th>
<th>28-Jul-01 Topside Profile 161-301 km</th>
<th>29-Jul-01 Full Profile 112-278 km</th>
<th>29-Jul-01 Topside Profile 161-278 km</th>
<th>30-Jul-01 Full Profile 112-301 km</th>
<th>30-Jul-01 Topside Profile 161-301 km</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( O_2=10 ) CSD</td>
<td></td>
<td>67.1</td>
<td>62.4</td>
<td>49.7</td>
<td>42.0</td>
<td>22.8</td>
<td>21.2</td>
</tr>
<tr>
<td></td>
<td>( CSD+ICE )</td>
<td></td>
<td>56.4</td>
<td>52.2</td>
<td>44.5</td>
<td>36.8</td>
<td>25.1</td>
<td>18.2</td>
</tr>
<tr>
<td></td>
<td>( O_2=15 ) CSD</td>
<td></td>
<td>95.8</td>
<td>63.5</td>
<td>53.0</td>
<td>35.4</td>
<td>24.3</td>
<td>22.9</td>
</tr>
<tr>
<td></td>
<td>( CSD+ICE )</td>
<td></td>
<td>82.7</td>
<td>51.5</td>
<td>39.6</td>
<td>29.5</td>
<td>17.6</td>
<td>16.4</td>
</tr>
<tr>
<td></td>
<td>( O_2=20 ) CSD</td>
<td></td>
<td>160.0</td>
<td>53.1</td>
<td>60.3</td>
<td>31.7</td>
<td>31.3</td>
<td>21.3</td>
</tr>
<tr>
<td></td>
<td>( CSD+ICE )</td>
<td></td>
<td>132.9</td>
<td>41.8</td>
<td>53.8</td>
<td>25.9</td>
<td>24.7</td>
<td>14.4</td>
</tr>
<tr>
<td>Hinteregger scaling=1</td>
<td>( O_2=10 ) CSD</td>
<td></td>
<td>66.8</td>
<td>60.7</td>
<td>47.7</td>
<td>42.2</td>
<td>26.0</td>
<td>23.7</td>
</tr>
<tr>
<td></td>
<td>( CSD+ICE )</td>
<td></td>
<td>55.8</td>
<td>50.7</td>
<td>42.3</td>
<td>35.0</td>
<td>21.9</td>
<td>17.7</td>
</tr>
<tr>
<td></td>
<td>( O_2=15 ) CSD</td>
<td></td>
<td>99.6</td>
<td>61.9</td>
<td>48.7</td>
<td>35.3</td>
<td>24.4</td>
<td>22.4</td>
</tr>
<tr>
<td></td>
<td>( CSD+ICE )</td>
<td></td>
<td>86.3</td>
<td>50.1</td>
<td>41.1</td>
<td>29.6</td>
<td>17.8</td>
<td>16.0</td>
</tr>
<tr>
<td></td>
<td>( O_2=20 ) CSD</td>
<td></td>
<td>167.7</td>
<td>52.0</td>
<td>63.5</td>
<td>31.6</td>
<td>32.8</td>
<td>20.7</td>
</tr>
<tr>
<td></td>
<td>( CSD+ICE )</td>
<td></td>
<td>138.8</td>
<td>40.8</td>
<td>57.1</td>
<td>26.0</td>
<td>25.0</td>
<td>13.9</td>
</tr>
<tr>
<td>Hinteregger scaling=2</td>
<td>( O_2=10 ) CSD</td>
<td></td>
<td>67.5</td>
<td>59.0</td>
<td>46.6</td>
<td>41.1</td>
<td>23.5</td>
<td>22.9</td>
</tr>
<tr>
<td></td>
<td>( CSD+ICE )</td>
<td></td>
<td>56.2</td>
<td>49.4</td>
<td>41.2</td>
<td>35.3</td>
<td>19.4</td>
<td>17.1</td>
</tr>
<tr>
<td></td>
<td>( O_2=15 ) CSD</td>
<td></td>
<td>103.8</td>
<td>60.2</td>
<td>50.5</td>
<td>35.3</td>
<td>24.9</td>
<td>21.8</td>
</tr>
<tr>
<td></td>
<td>( CSD+ICE )</td>
<td></td>
<td>90.3</td>
<td>48.8</td>
<td>43.0</td>
<td>29.7</td>
<td>18.4</td>
<td>15.6</td>
</tr>
<tr>
<td></td>
<td>( O_2=20 ) CSD</td>
<td></td>
<td>156.6</td>
<td>50.9</td>
<td>67.0</td>
<td>31.1</td>
<td>34.5</td>
<td>20.2</td>
</tr>
<tr>
<td></td>
<td>( CSD+ICE )</td>
<td></td>
<td>145.0</td>
<td>40.0</td>
<td>60.7</td>
<td>26.2</td>
<td>25.7</td>
<td>13.5</td>
</tr>
<tr>
<td>Hinteregger scaling=3</td>
<td>( O_2=10 ) CSD</td>
<td></td>
<td>84.3</td>
<td>43.1</td>
<td>45.2</td>
<td>39.0</td>
<td>21.7</td>
<td>21.6</td>
</tr>
<tr>
<td></td>
<td>( CSD+ICE )</td>
<td></td>
<td>72.4</td>
<td>36.5</td>
<td>39.8</td>
<td>34.1</td>
<td>17.6</td>
<td>16.6</td>
</tr>
<tr>
<td></td>
<td>( O_2=15 ) CSD</td>
<td></td>
<td>156.1</td>
<td>37.8</td>
<td>59.9</td>
<td>37.4</td>
<td>29.2</td>
<td>20.7</td>
</tr>
<tr>
<td></td>
<td>( CSD+ICE )</td>
<td></td>
<td>124.2</td>
<td>34.6</td>
<td>52.2</td>
<td>32.9</td>
<td>22.5</td>
<td>14.8</td>
</tr>
<tr>
<td></td>
<td>( O_2=20 ) CSD</td>
<td></td>
<td>165.7</td>
<td>79.0</td>
<td>57.5</td>
<td>31.5</td>
<td>42.9</td>
<td>18.8</td>
</tr>
<tr>
<td></td>
<td>( CSD+ICE )</td>
<td></td>
<td>150.6</td>
<td>64.9</td>
<td>59.6</td>
<td>30.1</td>
<td>35.5</td>
<td>12.7</td>
</tr>
</tbody>
</table>

Scaled [Solomon et al., 2001]
Table 3-2. A summary of best fit parameters from Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Full Profile (~112-300 km)</th>
<th>Topside Profile (~161-300 km)</th>
<th>Total (Topside and Full Profile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSD alone</td>
<td>2/36 = 5.6%</td>
<td>0/36 = 0.0%</td>
<td>2/72 = 2.8%</td>
</tr>
<tr>
<td>CSD+ICE</td>
<td>34/36 = 94.4%</td>
<td>36/36 = 100.0%</td>
<td>70/72 = 97.2%</td>
</tr>
<tr>
<td>$\sigma_{O_2} = 10 \times 10^{-18}$ cm$^2$</td>
<td>18/24 = 75.0%</td>
<td>1/24 = 4.2%</td>
<td>19/48 = 39.6%</td>
</tr>
<tr>
<td>$\sigma_{O_2} = 15 \times 10^{-18}$ cm$^2$</td>
<td>6/24 = 25.0%</td>
<td>2/24 = 8.3%</td>
<td>8/48 = 16.7%</td>
</tr>
<tr>
<td>$\sigma_{O_2} = 20 \times 10^{-18}$ cm$^2$</td>
<td>0/24 = 0.0%</td>
<td>21/24 = 87.5%</td>
<td>21/48 = 43.8%</td>
</tr>
<tr>
<td>Hinteregger x 1</td>
<td>3/18 = 16.7%</td>
<td>8/18 = 44.4%</td>
<td>11/36 = 30.6%</td>
</tr>
<tr>
<td>Hinteregger x 2</td>
<td>0/18 = 0.0%</td>
<td>3/18 = 16.7%</td>
<td>3/36 = 8.3%</td>
</tr>
<tr>
<td>Hinteregger x 3</td>
<td>4/18 = 22.2%</td>
<td>2/18 = 11.1%</td>
<td>6/36 = 16.7%</td>
</tr>
<tr>
<td>Solomon et al.</td>
<td>11/18 = 61.1%</td>
<td>5/18 = 27.8%</td>
<td>16/36 = 44.4%</td>
</tr>
</tbody>
</table>
When examining the full profile, scaling the Hinteregger flux in three separate energy regions, as suggested by Solomon et al. (2001), yields the lowest chi-square values in 11 of the 18 cases. The higher energy photons resulting from the approach by Solomon et al. penetrate the atmosphere more deeply and have a greater effect on the full profile. When analyzing the topside only, the approach by Solomon et al. returns the lowest chi-square value in 5 of 18 cases, and the lowest Hinteregger scaling (scaling=1) results in the best fit in 8 of 18 cases.

3.4. Conclusion

Comparisons of limb profiles from satellite observations and model calculations of the N₂ LBH emissions showed better agreement in 34 of 36 cases when cascading between the singlet states was included. These results are consistent with those of Cartwright (1978), Budzien et al. (1994), Eastes and Dentamaro (1996), and Eastes (2000), all of whom have suggested cascade may play a significant role in the excitation of N₂ LBH emissions.

Comparisons of observed and calculated LBH profiles indicate the temperature dependence of the O₂ cross section should be included to obtain the most accurate results. An O₂ cross section of 10 x 10^{-18} cm² provided the lowest chi-square for the full profile (112-300 km), but for the topside (161-300) a cross section of 20 x 10^{-18} cm² gave better fits. This change is consistent with both the findings of Kanik et al. [1997] and Yoshino et al. [2005], who found higher cross sections at higher temperatures.

To examine the effects of changes in the solar EUV and soft X-ray spectrum, the solar spectrum used in the model calculations was scaled using four different approaches. All the spectra began with Hinteregger’s empirical algorithm for the solar spectrum. This spectrum was used both without scaling and with wavelengths at energies greater than 88 eV were increased by
2 or 3 respectively. A fourth solar spectrum [Solomon et al., 2001], used separate scaling factors for three different wavelength ranges. The latter, which is based on more recent measurements of the solar irradiance, yielded the best results. This suggests, as expected, that improvements in the solar spectrum used in the model calculations improves agreement with the observations.
4. REMOTE SENSING OF NEUTRAL TEMPERATURES

This chapter presents remotely sensed neutral temperatures from observations at a fixed tangent altitude. Latitudinal profiles of the temperatures are obtained by inversion of the (1-1) Lyman-Birge-Hopfield (LBH) band of N\textsubscript{2} using high-resolution spectra obtained from the HITS instrument aboard ARGOS. Observed temperatures are compared with those obtained from two calculations using the MSIS 2000 model. In the first temperatures are calculated using F10.7, F10.7 81 day average, and Ap for the averaged latitude and averaged local time of the HITS observations. In the second, MSIS neutral densities were constrained to match densities derived from satellite drag data, and the corresponding neutral temperatures are used. The temperatures determined from LBH spectra agree best with those derived from MSIS when it is constrained to match the satellite drag data. Results indicate that current instrumentation and fitting techniques are capable of remotely sensing thermospheric temperature.

4.1. Introduction

Earth’s thermosphere is dynamic and responds within hours to changes in both solar irradiance and geomagnetic activity. Understanding the variation of neutral temperature (T\textsubscript{n}) profile in the thermosphere is a key to understanding space weather. While it is of key importance, temperature data for some parts of the atmosphere, such as the lower thermosphere (100-200 km), is insufficient for understanding the changes seen in the thermosphere and ionosphere. Accurate mapping of neutral temperatures at global scales will allow the thermospheric response to solar and geomagnetic changes to be observed and understood.
Measurements of the thermosphere may be conducted either directly or remotely. Accurate direct measurements are difficult to obtain due to the low density of the thermosphere and such measurements are geographically localized. Radar techniques can be used in the daytime, but the instrumentation is large, expensive and consequently has limited availability, and all ground based measurements are spatially localized and provide limited coverage over the oceans. While ground based, optical remote sensing is possible, UV emissions from the dayglow, which provide more direct information about the conditions and processes in the upper atmosphere, are absorbed by O$_2$ at altitudes below 100 km and can only be observed from space. To fully measure the spatial dynamics of the upper atmosphere UV dayglow should be obtained global coverage. This global perspective can be provided by UV remote sensing (Figure 4.1), and the LBH bands are one of the two emissions typically used for UV remote sensing of the space environment.

This chapter presents rotational temperatures in the lower thermosphere obtained through inversion of N$_2$ LBH emissions. The emissions are from HITS aboard ARGOS (Figure 4.2), and were gathered throughout a range of latitudes during 15 days in 2000 and 2001. Rotational temperatures obtained in this way show good agreement with neutral temperatures derived from other measurements.

4.2. Inversion Technique

During inversion, the observations are modeled using a set of $n$ parameters. These parameters are varied systematically, and the resulting model is compared to the observed data to find the set of parameters that minimize chi squared. The model that best fits the observation contains optimal values for the $n$ parameters.
Figure 4-1. A global perspective such as the one shown can only come from remotely sensed satellite data. The LBH emissions, which are caused by photoelectrons, are prevalent in the southern hemisphere in this composite image formed by combining data from 15 orbits. (Image courtesy Johns Hopkins Applied Physics Lab)
Figure 4-2. The ARGOS spacecraft in final preparation for launch atop its Delta II launch vehicle, at Vandenberg AFB, CA in January, 1999. Launched on 23 February 1999 ARGOS carried the High-resolution Ionospheric and Thermospheric Spectrograph (HITS), a very high resolution (> .5 Å over a 500-1500 Å passband) Rowland circle spectrograph. (Image courtesy Naval Research Lab)
At sufficient spectral resolution (~2 Å for the LBH bands) the band shape of molecular emissions contains temperature information. As the gas temperature increases, the rotational temperature does also, increasing the populations of higher rotational quantum states (Figure 4.3). In one study of the LBH bands of N₂ (Aksnes et al., 2006), these rotational temperatures have been shown to have reasonable agreement with the neutral temperatures.

The temperature information contained in Earth’s N₂ LBH dayglow, through broadening of the bands, can be extracted. To extract the temperature information, the observed emissions can be approximated as the sum of many emissions along the LOS, each with an associated altitude, brightness, and temperature (Figure 4.4). Photoabsorption by O₂ must be included in the calculation as well, and those emissions furthest from the observation point are attenuated most. These individual emissions must be modeled, weighted to account for both volume emission rate and absorption, and summed to model the spectra.

The first step in fitting a model to the observations is to establish the background of the observed spectra. The LBH emission is responsible for emissions throughout the observed passband. The perceived background is therefore dependent on the brightness of the LBH emission. The approximated spectrum is subtracted from the observed spectrum, and what is left should be the background. This process is iterated using the best fit spectra and background estimate, which is then used to find the best fit spectra, until the process converges. Parameters used in this step are atomic nitrogen emission at 1493 Å, instrument sensitivity, emission from v=0,1,2,3,4,5, and 6 LBH bands, O₂
Figure 4-3. Broadening of the (1-1) emission with increased rotational temperature enables remote sensing of rotational temperatures in the thermosphere. Aksnes (2006) found good agreement between neutral temperatures from models and rotational temperatures for the LBH emissions observed on three geomagnetically calm days in July 2001. Note that the fitting performed in this study only fits the (1-1) band up to 1470 Å (the vertical dotted and dashed line) due to the proximity of the (5-4) band.
Figure 4-4. The Figure above illustrates the superposition of spectra used to produce a single, synthetic spectrum. Each of the spectra along the line of sight have a slightly different temperatures and consequently slightly different spectra. The greater the distance to the observation point, the greater the attenuation, and the less the contribution to the observed brightness.
photoabsorption cross section, wavelength calibration, rotational temperature (described below), and a uniform background. The entire passband (1440-1545 Å) is fitted to approximate these parameters (Figure 4.5).

While the observed spectrum is the sum of spectra from all the temperatures along the line of sight, the initial fitting described above uses a single temperature. The next step is to fit the LBH (1,1) band while incorporating the variation in temperature and brightness along the line of sight. This superposition of multiple spectra, fitted to the observed spectrum can provide the temperature at altitudes along the LOS.

Figure 4.5 illustrates a typical spectrum in the 1440 – 1550 Å passband. The observed LBH (1-1) emission (the brightest emission in the passband) located at 1465 Å is fit to a synthetic spectrum to extract the temperature, and the Intrasysem Cascade Excitation (ICE) model (Eastes, 2000) is used to calculate the LBH volume emission rates used in the fit.

To model LBH volume emission rates the ICE model requires a model atmosphere and volume excitation rates for the modeled atmosphere. The Mass Spectrometer and Incoherent Scatter (MSIS 2000) model is used to model the atmosphere. MSIS incorporates pertinent information describing the HITS observations (date, latitude, local time) as well as geomagnetic conditions (Ap). The solar conditions input into MSIS (F10.7 and F10.7 average) are variable parameters for the inversion, and will be adjusted to affect a change atmospheric temperature profile. This will change the synthetic spectrum.
Figure 4-5. A typical spectrum in the 1440 – 1550 Å passband. The dashed line is the fitted background. The solid red line is the first pass model fit to the spectrum. The prominent bands are annotated with the vibrational states (initial-final). The LBH (1-1) band is the brightest LBH emission in the passband, and by fitting a superposition of spectra constructed using the ICE model the temperature is extracted.
This atmosphere is then used by the Continuous Slowing Down (CSD) model (Jasperse, 1976) to calculate volume excitation rates for the $^1\Pi_g$ state. The final LBH volume emission rates which correspond to the MSIS atmosphere and the CSD direct excitation are then calculated using ICE (Eastes, 2000).

Using the average tangent altitude of the HITS observations and an observer altitude of 400 km, these modeled volume emission rates are integrated along the LOS and fit to the observations. The LBH (1-1) spectra is modeled at 30 km steps along the LOS. Each step along the LOS has a corresponding altitude, LBH volume emission rate, and temperature. The area under each of the modeled (1-1) spectra is normalized to one, to ensure that only the shape of the (1-1) spectra is determined in this step. Each normalized spectra is then multiplied by the brightness calculated for the (1-1) band at that altitude and attenuated to account for photoabsorption along the line of sight to the observer (HITS on ARGOS). These individual spectra, one for each step along the LOS, are summed. This sum of all spectra along the LOS is the modeled spectrum for a given tangent altitude. This process is iterated adjusting the F10.7 and F10.7 average, and comparing the resulting modeled spectra to the observation until the iteration converges. Using this technique, modeled spectra are fitted to the LBH (1-1) observations.

The modeled LBH volume emission array described above, and resulting synthetic spectra, both depend on the modeled atmosphere used in the CSD+ICE model. Increasing or decreasing the solar parameters (F10.7 and F10.7 81 day average) changes the temperature throughout the altitude range. This changes the modeled spectra. The resulting fit utilizes the physics responsible for the observations (attenuated emissions through the LOS), and provides temperatures throughout the range of altitudes rather than at just one altitude.
4.3. **Comparison**

Temperatures obtained from inversion of observed LBH spectra are compared with temperatures from the MSIS 2000 model and with temperatures from the MSIS model constrained using satellite drag data (Figure 4.6). While both techniques use the MSIS 2000 (Picone et al., 2002) model and utilize the positional information describing the HITS observation (latitude, local time, date), different solar parameters are used. One of the comparisons uses the average and daily solar parameters (F10.7 and F10.7 average) representative of the observation date. When the MSIS model is constrained by the satellite drag measurements, solar parameters have been varied in order to fit the MSIS neutral densities to densities obtained from the drag data of twelve satellites at orbital perigees ranging from ~200 to 400 km.

When using the MSIS model, the date, F10.7, F10.7 average, Ap, latitude, longitude, and universal time for each data point shown in Figure 4-2 is used when modeling the observation. The resulting neutral temperatures are calculated at an altitude of 180 km and compared against the temperatures extracted from the HITS spectra at 180 km altitude.

4.4. **Satellite Drag Data**

Using the method of Bowman et al. (2004), orbital drag data obtained from satellites in elliptical orbits is used to create densities for each of the fifteen days studied. The drag data are averaged values obtained over a range of altitudes and latitudes; however; the orbits are
Figure 4-6. Neutral temperatures from 24 July 2001 obtained by inversion of high resolution satellite observations of N₂ LBH emissions (X), MSIS constrained by drag data (triangle), and MSIS (square). The dotted is counts = 300. All spectra with counts ≥ 600 = 600. Notice the two spectra with the lowest counts lie well outside the other data points illustrating the error associated with low counts.
sufficiently elliptical to ensure that the drag and consequent density calculations are spatially localized.

As a satellite in elliptical orbit encounters a homogenous atmosphere, the instantaneous drag is greatest at closest approach. The majority of the drag experienced in an orbit is localized over a fraction of the orbit. This fractional drag versus latitude was examined by Marcos et al. (2006). The results of the study for orbits with 90 degree inclination, perigee of 350 km, average solar flux (F10.7 = 150), and apogee ranging from 1000 to 5000 km are outlined in Figure 4.7. Choosing only elliptical orbits allows the designation of altitude, latitude and local time to the calculated satellite density values.

4.5. Sources of Observational Error

The ARGOS satellite experienced a GPS failure early in the mission and alternative sources of pointing information had to be established. In addition, the HITS instrument experience a software glitch that compromised the signal to noise of the data for some time. These issues were addressed and measurements were taken from May of 1999 until late 2001.

Early in the ARGOS mission a firmware error resulted in the software discarding about half the counts, as a result of this error HITS spectra obtained before July of 2001 have a lower signal to noise. A firmware upgrade on July 2001 improved the data quality. Unfortunately, the majority of the dates for which we have satellite drag data are prior to the firmware update.

Results indicate as signal to noise greater than 300 at the peak of the (1-1) emission is needed, and to obtain consistent results Tables 1 - 4 indicate the maximum number of counts in the range of the LBH (1-1) fit (1460 – 1470 Å) should be > 400. The number of individual spectra meeting this criterion is 25% of the unsmoothed spectra, and 19% of the smoothed
Figure 4-7. To retain some spatial information elliptical orbits are chosen. The figure above describes a satellite that reaches perigee at the equator. The apogee and perigee values for the different curves are listed in the legend (Marcos et al., 2006).
Table 4-1. Averaged (daily) modeled temperature profiles which best fit HITS data.

<table>
<thead>
<tr>
<th>Data used \ Model</th>
<th>Derive from drag data</th>
<th>SPIDR-MSIS</th>
<th>Percent of observations which fit drag data derivation best</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>7 days</td>
<td>8 days</td>
<td>46.7%</td>
</tr>
<tr>
<td>(1-1) Counts &gt; 100</td>
<td>8 days</td>
<td>7 days</td>
<td>53.3%</td>
</tr>
<tr>
<td>(1-1) Counts &gt; 200</td>
<td>9 days</td>
<td>6 days</td>
<td>60.0%</td>
</tr>
<tr>
<td>(1-1) Counts &gt; 300</td>
<td>7 days</td>
<td>5 days</td>
<td>58.3%</td>
</tr>
<tr>
<td>(1-1) Counts &gt; 400</td>
<td>8 days</td>
<td>3 days</td>
<td>67.6%</td>
</tr>
<tr>
<td>(1-1) Counts &gt; 500</td>
<td>6 days</td>
<td>1 days</td>
<td>80%</td>
</tr>
</tbody>
</table>
Table 4-2. Same as Table 1 but with smoothed spectra, (average every five spectra)

<table>
<thead>
<tr>
<th>Data used \ Model</th>
<th>Derive from drag data</th>
<th>SPIDR-MSIS</th>
<th>Percent of observations which fit drag data derivation best</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>12 days</td>
<td>3 days</td>
<td>80.0%</td>
</tr>
<tr>
<td>(1-1) Counts &gt; 100</td>
<td>11 days</td>
<td>4 days</td>
<td>73.3%</td>
</tr>
<tr>
<td>(1-1) Counts &gt; 200</td>
<td>9 days</td>
<td>6 days</td>
<td>60.0%</td>
</tr>
<tr>
<td>(1-1) Counts &gt; 300</td>
<td>9 days</td>
<td>3 days</td>
<td>75.0%</td>
</tr>
<tr>
<td>(1-1) Counts &gt; 400</td>
<td>8 days</td>
<td>1 days</td>
<td>88.9%</td>
</tr>
<tr>
<td>(1-1) Counts &gt; 500</td>
<td>7 days</td>
<td>0 days</td>
<td>100.0%</td>
</tr>
</tbody>
</table>
Table 4-3. Number of Individual spectra from each technique which best fit HITS data

<table>
<thead>
<tr>
<th>Data used \ Model</th>
<th>Derive from drag data</th>
<th>SPIDR-MSIS</th>
<th>Percent of observations which fit drag data derivation best</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1-1) All</td>
<td>85</td>
<td>54</td>
<td>61.2%</td>
</tr>
<tr>
<td>(1-1) Counts &gt; 100</td>
<td>67</td>
<td>42</td>
<td>61.5%</td>
</tr>
<tr>
<td>(1-1) Counts &gt; 200</td>
<td>48</td>
<td>30</td>
<td>61.5%</td>
</tr>
<tr>
<td>(1-1) Counts &gt; 300</td>
<td>28</td>
<td>18</td>
<td>60.9%</td>
</tr>
<tr>
<td>(1-1) Counts &gt; 400</td>
<td>23</td>
<td>11</td>
<td>67.6%</td>
</tr>
<tr>
<td>(1-1) Counts &gt; 500</td>
<td>12</td>
<td>3</td>
<td>80.0%</td>
</tr>
</tbody>
</table>
Table 4-4. Smoothed spectra used to produce Table 1.

<table>
<thead>
<tr>
<th>Data used \ Model</th>
<th>Derive from drag data</th>
<th>SPIDR-MSIS</th>
<th>Percent of observations which fit drag data derivation best</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>86</td>
<td>53</td>
<td>61.9%</td>
</tr>
<tr>
<td>(1-1) Counts &gt; 100</td>
<td>58</td>
<td>41</td>
<td>58.6%</td>
</tr>
<tr>
<td>(1-1) Counts &gt; 200</td>
<td>41</td>
<td>29</td>
<td>58.6%</td>
</tr>
<tr>
<td>(1-1) Counts &gt; 300</td>
<td>29</td>
<td>16</td>
<td>64.4%</td>
</tr>
<tr>
<td>(1-1) Counts &gt; 400</td>
<td>20</td>
<td>7</td>
<td>74.1%</td>
</tr>
<tr>
<td>(1-1) Counts &gt; 500</td>
<td>13</td>
<td>1</td>
<td>92.9%</td>
</tr>
</tbody>
</table>
spectra. This difference is due to the averaging of the peak value during the smoothing process. For example Figure 4.9 has an absolute peak of about 770 counts but the average value for the highest 5 values is around 700. The averaging process (smoothing) decreases the peak value. Figures 4.8 and 4.9 contrast high and low maximum counts, and provide a reference for the signal to noise needed to determine spectral broadening.

An additional source of error within the HITS data is uncertainty in the tangent altitude. ARGOS, and consequently HITS, was unable to accurately determine altitude and pointing direction due to an instrumentation failure. The inversion of HITS spectra requires a priori knowledge of observer position and tangent altitude (in order to create a line-of-sight). To approximate the required tangent altitude to within ~10 km we used altitude profiles from companion instrument also aboard ARGOS, the Low Resolution Airglow and Aurora Spectrograph (LORAAS). LORAAS rather scanned the limb while HITS was in stare mode. The peak of the altitude profile produced by LORAAS limb scan was used for altitude calibration.

The peak brightness of LORAAS altitude profile should occur near 145 km. The difference (145 – altitude of the observed peak) was used as an altitude correction for the HITS spectra in this chapter. Figure 4.9 shows a day (13 November 2000) for which HITS and LORAAS are in limb scan mode. The plot illustrates the probable pointing error. The peak of the observed emission occurs near 100 km, the peak should be nearer 145±10 km.
Figure 4-8. In the 1462-1470 Å wavelength range, a maximum count of less than 100 does not provide the signal to noise necessary to accurately determine broadening due to rotational temperature.
Figure 4-9. A higher maximum count reduces the relative uncertainty through the wavelength bins and allows the broadening due to rotational temperature to be more closely determined than the spectra in the previous Figure.
4.6. Results

With sufficient signal to noise (Figure 4.6 bottom) temperatures extracted from HITS spectra agree more closely with temperatures derived from satellite drag data than with the MSIS model. As the peak number of counts detected increases, the fraction of spectra that fit the drag data more closely increases. If all individual spectra are considered, regardless of the number of counts, the drag data fits best in 85 of 139 cases. If the only spectra considered are those in which the peak number of counts between 1460 and 1470 Å is greater than 100, the drag data fits best in 67 of 109 cases. If only spectra containing counts greater than 500 are considered HITS fits more closely with the drag data in 12 of 15 cases. The same effect is observed within the individual data sets. The data for 24 July 2001 (Figure 4.10) illustrates this point well. The two points with the lowest counts (-11 latitude and 22 latitude) are the two points which lie well off the observed trend.

Figure 4.10 shows a plot of neutral temperatures obtained by inversion of HITS dayglow spectra (X symbol) on one of the fifteen days included in this study (24 July 2001). The values plotted are the fitted rotational temperatures at an altitude of 180 km; however, in creating a superposition of many spectra along the LOS, temperatures were calculated at many points and could have been presented for any altitude included in the MSIS model. For purposes of comparison, two different techniques are used to model the neutral temperatures; both are presented along with the remotely sensed rotational temperatures. Although rotational temperatures are obtained through the inversion of LBH emissions, it has been shown that these
Figure 4-10. In the image above the peak of the observed emissions should occur near 145 km, it is reported as ~ 100 km. To ensure uniformity in this study the altitude of peak emission in the 1440-1550 Å passband was adjusted to occur near 145 km.
rotational temperatures agree with neutral temperatures in a three day sample (Aksnes, 2006). This technique of superposition of spectra along the line of sight has not been applied to LBH emissions before this study.

4.7. Conclusion

Neutral temperatures obtained from high resolution spectra of LBH emissions, show close agreement to temperatures interpreted from satellite drag data than to MSIS temperatures. The 1.3 Å (FWHM) resolution afforded by HITS is sufficient for temperature determination using the (1-1) LBH band of N₂. When the peak number of counts in the 1460 – 1470 Å range exceeds 300, the remotely sensed temperatures show consistent agreement with temperatures extrapolated from satellite drag measurements. This indicates that currently existing instrumentation and the inversion technique used are capable of remotely sensing thermospheric temperatures.
5. SUMMARY

LBH emissions in Earth’s UV dayglow are produced by photoelectron impact excitation of the N₂ a \(^{1}\Pi \text{g}\) state and contain direct information about the thermospheric composition. Modern inversion techniques strive to extract the, temperature and absolute concentrations of the principle atmospheric constituents through these LBH emissions, or the attenuation of these emissions as is the case with photoabsorption of O₂. To accurately model the emissions a full understanding of the causal mechanism is crucial as are accurate values for parameters such as cross section, and solar irradiance spectrum.

O₂ affects the observed LBH spectrum through photoabsorption. Utilizing this absorption in an inversion model obviously requires incorporating the variation of density with altitude, but variation of the O₂ cross section with temperature also has a measurable effect on the resulting LBH emission profile and must be considered. This study has demonstrated the effect of photoabsorption and the variation of photoabsorption with altitude on the LBH profile.

Utilizing observed LBH dayglow emissions to create profile of brightness through the atmosphere is straightforward. The physical constants and mechanisms required to invert these observations (cross sections, cascading, and temperature dependence) have or will be measured to sufficient accuracy for inversion purposes. To invert the observations accurately, the solar irradiance spectrum must be quantified at the time of the observations. Increases in solar soft X-ray and EUV decrease LBH profile peak position and change the shape of the observed LBH profile. Measurement of high resolution LBH spectra, obtained globally, and simultaneously measured solar irradiance are crucial to construction of accurate models.
The mechanism for the excitation of the LBH emissions is electron impact excitation by photoelectrons; however, to accurately describe the emission brightness and profile shape cascading between adjacent singlet states is important, and increases the total brightness by a factor of about 1.5. Incorporating these factors, cascading, photoabsorption, and solar irradiance, will allow accurate modeling of the LBH dayglow emission. Applying this model in an inversion with high resolution spectroscopic observations and simultaneously obtained solar irradiance measurements will enable accurate remote temperature sensing of the thermosphere.
FORTRAN Program : QMPI

This program reads electron energy grid, photoionization cross sections, photoabsorption cross sections, and solar flux. If solar flux is Hinteregger reference flux (sc#21refw) then the Hinteregger algorithm is applied with the parameters read from PHIN.DAT. All these pieces are incorporated in preparation for calculating the photoelectron production.

The unformatted file produced, PIX.UNF contains the solar irradiance used by CSD and ICE to produce LBH emissions. Changes in the solar irradiance affecting the LBH emissions must be made in this program to be applied later.

Main programs and files accessed:

QXCSD.DAT-input file(electron energy grid)
QXPI.DAT-input file(photo cross sections)
SFLUX.DAT-input file(solar flux before any algorithm is applied)
PHIN.DAT-formatted input file (positional and solar parameters)
PIX.UNF-unformatted output file (solar flux after algorithm is applied)

Usage: The solar information (F10.7, F10.7 average) is input through PHIN.DAT. The first line of the formatted input file SFLUX.DAT contains a value read in as variable ISW in the program (QMPI) which acts as a switch to tell the program which scaling to use. A value of 3 (ISW=3) uses Hinteregger flux with a scaling of 6, 4, and 5 respectively for the 2-7 nm, 6-19 nm, and 17-20 nm wavelength ranges as suggested by Solomon et al. (2001).
ISW = 5 uses no algorithm at all and reads in SFLUX.DAT as is, this is convenient when using flux files produced by other applications (for example AURIC). Lastly, a value of 6 uses the Hinteregger algorithm with a scaling factor (A) applied to all energies greater than (B). The values of A and B are read in from the first line of PHIN.DAT.

---------------------

FORTRAN Program: CSD+ICE

This program is run after QMPI and uses the output file produced by QMPI (PIX.UNF).

Purpose: This program reads in the photoionization cross sections, solar flux, electron energy grid (from PIX.UNF), and various other necessary information to calculate the photoelectron flux. This flux is then applied to the modeled atmosphere with electron impact cross sections (from QGLOW.DAT). Transitions between populated singlet states (cascade) is then incorporated through rate constants within the program. The resulting LBH volume emission rates for vibrational levels 0-6 are output in the file TOUT.DAT.

Main programs and files accessed

'PHIN.DAT' - formatted input file (positional and solar parameters)

'PIX.UNF' - unformatted input written by qmpi (solar irradiance model, electron energy grid, photoionization cross sections).

'QGLOW.DAT' - airglow cross sections

'TOUT.DAT' - formatted output file

Usage: CSD is compiled along with MSIS and ICE. PHIN.DAT contains all input parameters. F10.7, F10.7 average, Ap, local time, latitude, and longitude. This is where the user inputs the
parameters describing the desired conditions. The output is a formatted table of LBH volume emission rates and their associated altitudes. The altitudes array is created by a data file within CSD. The LBH values are given individually for each vibrational level or as a total emission at altitude. The relative contributions from direct excitation, radiative cascade, collision induced electronic transitions, and the total emissions are given for each vibrational level as well.

----------------------------

IDL Programs: READ_TOUT & LOS_TOUT

These programs are run after CSD+ICE and use the output file produced by CSD+ICE (TOUT.DAT).

Purpose: To read the formatted output file TOUT.DAT and integrate the LBH emission along a line of sight. In addition, a spectrum is produced representing the (1-1) emission along the line of sight.

TOUT.DAT (formatted input)

ICE (IDL structure output)

Usage: These two programs are run from within IDL. They must be run consecutively, first READ then LOS. READ_TOUT reads the V=1 band information from TOUT.DAT at which time LOS_TOUT is run. LOS_TOUT integrates the LBH v=1 emission through a line of sight given a tangent altitude and an observer altitude. The result is a brightness associated with a tangent altitude. The program also creates a synthetic spectrum between 1462 and 1470 Å. This corresponds to the LBH (1-1) band which is the brightest band in the 1440-1450 Å passband measured by HITS.

-------------------------------------
IDL Program: PROCESS_HITS

This program reads, collates, coadds and filters the HITS structure from the Naval Research Lab. The program contains an altitude array which will be used to bin the tangent altitude values from HITS. The size of the altitude bins is changed from within this program by changing the variable altgrid. Hotspots on the detector are filtered out as are auroral emissions which saturate the spectra.

Main programs and files accessed:

**HYYYY_MM_DD.XDR** (IDL structure input [HITS data year_month_day])

**HYYYY_MM_DDmk.XDR** (IDL array input)

**HYYYY_MM_DD_SPECTRA.XDR** (IDL structure output)

Usage: Upon execution the program is interactive and displays a histogram of the dayspectra for each altitude bin. The user must use a mouse and click on the histogram to advance to the next bin. The mask files (*mk.xdr) are produced separately and prior to execution are called (restored) into the program

-----------------------------

IDL Program: FIT_VIB_DIST

This program is run after PROCESS_HITS and uses the output file produced by PROCESS_HITS (HYYYY_MM_DD_SPECTRA.XDR)

This program inverts the HITS LBH spectra in the 1440-1550Å passband. The entire observed spectrum is fit with a model to estimate the brightness of each emission. The background estimate is then improved and the process iterates until it converges.

Main programs and files accessed:
**HYYY_MM_DD_SPECTRA.XDR** (IDL structure input)

**V_OUT.SAV** (IDL output structure)

Usage: Upon execution the program prompts the user for the year, month, and day of the observation (yyyy,mm,dd). The program looks in the appropriate directory and finds the spectra file and returns a structure with the relative brightness of each of the LBH vibrational levels in the passband.

-----------------------------

**IDL Program SVD_FIT**

This program requires an observation in the form of a limb scan spectra (*_spectra.xdr) produced as described earlier using PROCESS_HITS, and a line of sight profile produced using QMPI → (CSD+ICE) → READ_TOUT → LOS_TOUT. The model is given parameters in PHIN.DAT corresponding to the conditions at the time of the HITS observation, variations of these parameters can be used to investigate the effect on the resulting fit (eg. different solar irradiance). The program subtracts the background from the observed spectra and scales the observation peak value to 1. The program then scales the model and shifts the altitude grid to align the model and observation and performs a chi squared comparison. The best fit value for any set of parameters can be compared to the best fit using a different set of parameters. This technique was used to produce Table 3.1, varying O2 cross section, solar irradiance, and using ICE.
REFERENCES


Eastes, R. W., and A. V. Dentamaro (1996), Collision-induced transitions between the a '¹Πg, a' '¹Σu, and w '¹Δu states of N₂: Can they affect auroral N₂ Lyman-Birge-Hopfield band emissions?, J. Geophys. Res., 101, 26,931-26,940.


