# SOLAR IRRADIANCE AND THERMOSPHERIC AIRGLOW ROCKET EXPERIMENTS

**NASA Grant NAG5-5021 to the University of Colorado**
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## FINAL REPORT

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### 1. Summary

This report describes work done in support of the Solar Irradiance and Thermospheric Airglow Rocket Experiments at the University of Colorado for NASA grant NAG5-5021 under the direction of Dr. Stanley C. Solomon. (The overall rocket program is directed by Dr. Thomas N. Woods, formerly at the National Center for Atmospheric Research, and now also at the University of Colorado, for NASA grant NAG5-5141.) Grant NAG5-5021 provided assistance to the overall program through analysis of airglow and solar data, support of two graduate students, laboratory technical services, and field support.

The general goals of the rocket program were to measure the solar extreme ultraviolet spectral irradiance, measure the terrestrial far-ultraviolet airglow, and analyze their relationship at various levels of solar activity, including near solar minimum. These have been met, as shown below. In addition, we have used the attenuation of solar radiation as the rocket descends through the thermosphere to measure density changes.

This work demonstrates the maturity of the observational and modeling methods connecting energetic solar photon fluxes and airglow emissions through the processes of photoionization and photoelectron production and loss. Without a simultaneous photoelectron measurement, some aspects of this relationship remain obscure, and there are still questions pertaining to cascade contributions to molecular and atomic airglow emissions. However, by removing the solar irradiance as an "adjustable parameter" in the analysis, significant progress has been made toward understanding the relationship of far-ultraviolet airglow emissions to the solar and atmospheric conditions that control them.

### 2. Rocket Flights and Instrumentation

Data from the following rocket flights were analyzed with support from this grant. All flights were from White Sands Missile Range near time of local noon. The first two flights were supported by an earlier grant, but analysis of data from them has continued under NAG5-5021.

Launch Dates

| *NASA Rocket #* | *Date* | $F_{10.7}$ |
|---|---|---|
| 36.098 | 27 October 1992 | 169 |
| 36.107 | 4 October 1993 | 121 |
| 36.124 | 3 November 1994 | 85 |
| 36.135 | 15 May 1997 | 74 |

Instrumentation Summary

| *Name* | *Acronym* | *Description* | *Purpose* |
|---|---|---|---|
| Solar EUV Grating Spectrometer | EGS | 1/4 meter normal incidence Rowland-circle spectrometer | Measure solar full-disk irradiance, 25–105 nm at ~0.2 nm resolution |
| Solar XUV Photodiodes | XPS | Metal-film coated silicon photodiode system | Measure solar full-disk irradiance, 2–30 nm at ~10 nm resolution |
| Solar X-ray Avalanche Photodiodes | AXS | Avalanche photodiode | Measure solar full-disk irradiance, 0.1–2 nm at ~0.1 nm resolution |
| Solar Lyman-α Ionization Cell | LYA | NO ionization cell | Measure solar full-disk irradiance at H Ly-α, 121.6 nm |
| FUV Airglow Spectrometer | AGS | f/3 Wadsworth spectrometer | Measure FUV airglow in local horizontal, 130–160 nm at ~0.4 nm resolution |
| Solar X-ray Imager | XUVI | 2-D solar X-ray imager | Image solar coronal emissions at 17 nm |
| Limb Camera | TVC | Commercial video camera | Measure limb alignment in visible; outreach support |

A solar gas ionization spectrograph payload from The University of California / Boston University (S. Chakrabarti, PI) was carried on the first two flights instead of the XRI. Modifications to several instruments were made during the course of the program, resulting in progressive improvement to the measurement suite, especially the XPS. The most significant modification was that the 1997 flight carried a new version of the EGS following loss of the original to the METEOR program. This new instrument is the protoflight version of the TIMED SEE EGS, and has an extended spectral range to 200 nm at the expense of lower (~0.4 nm) spectral resolution. The TIMED SEE XPS protoflight instrument, which has more diodes and a filter wheel mechanism, was also flown in 1997 instead of the original XPS.

## 3. Solar Measurements

A composite solar spectrum for 3 November 1994 is shown in Figure 1. Suborbital data are employed shortward of 105 nm; data from the SOLSTICE instrument on the Upper Atmosphere Research Satellite are used from 105–200 nm. This spectrum is representative of low solar activity conditions. The solar measurements are further described by *Woods et al.* [1998].

XUV measurements were analyzed by inferring spectral interval scale factors, as described by *Bailey et al.* [1998]. The following table summarizes the results. These scale factors are used as linear multipliers to the Hinteregger SC21REFW reference spectrum across the designated interval. No useful data were obtained from the 1992 flight (36.098) due to visible light leaks, but this problem was solved on subsequent flights.

XPS Spectral Interval Scale Factors

| $\lambda_{min}$ *(nm)* | $\lambda_{max}$ *(nm)* | *10/4/93 36.107* | *11/3/94 36.124* | *5/15/97 36.135* |
|---|---|---|---|---|
| 1.8 | 6.0 | 1.35 | 2.24 | 2.5 |
| 6.0 | 17.0 | – | 2.26 | – |
| 17.0 | 30.0 | 2.06 | 1.57 | 2.8 |

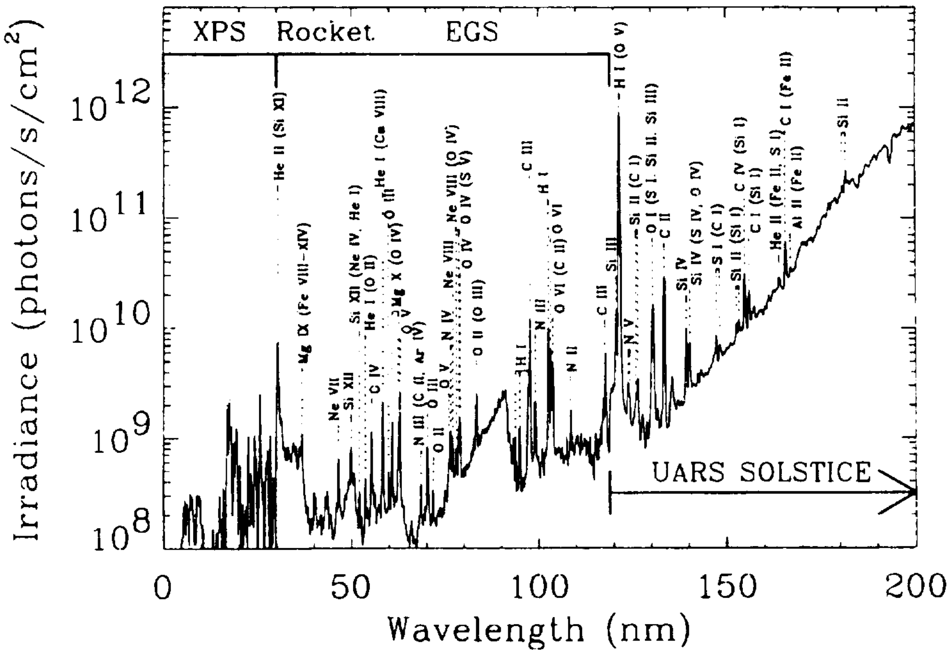


Figure 1. Solar spectrum measured by NASA Rocket 36.124 and by the UARS SOLSTICE instrument on 3 November 1994.

## 4. Atmospheric Analysis through Solar Attenuation

Thermospheric density can be inferred from the decreasing count rate at strong solar lines caused by absorption as the rocket descends through the atmosphere. When done near the center of the ionization continua, the result has small systematic error since the absorption cross sections are well-known. However, discrepancies between the predicted profile using the MSIS model atmosphere and the measured profile can be interpreted in several ways.

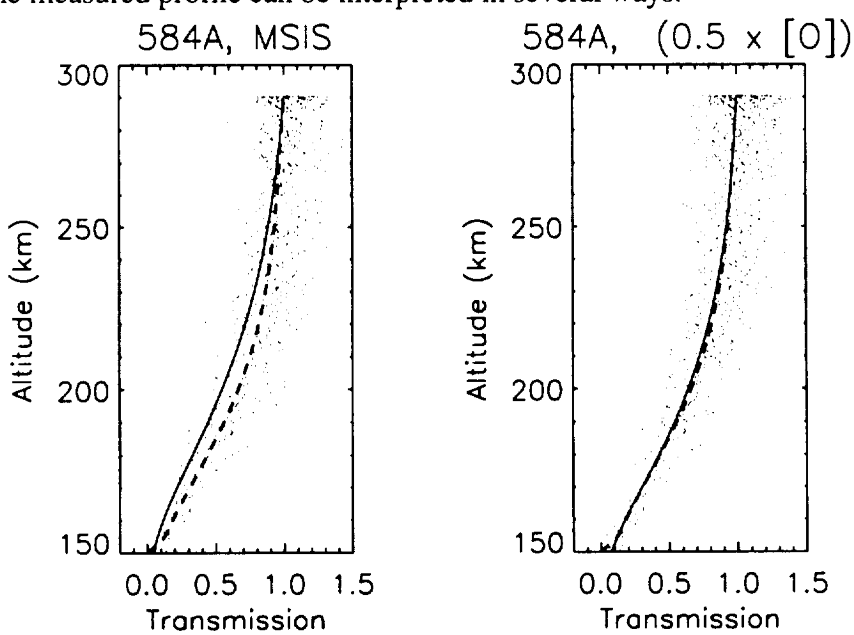


Figure 2. Attenuation profile of the HeI 58.4 nm solar line for the 10/4/93 flight, showing the data (dashed line) and model (solid line) for a standard MSIS atmosphere and one where the atomic oxygen density has been reduced by a factor of 0.5.

By reducing model atomic oxygen density, a better fit to the measurement can be obtained. A fit nearly as good can be obtained by drastically lowering the exospheric temperature in the model, or lowering the molecular nitrogen density. However, the conclusion that there is less column mass density above the rocket than the model predicts as it descends through ~200 km is inescapable. Since the attenuation measurement is based on count rate ratios, there can be no absolute calibration error. This measurement of decreased density is consistent for all of the flights analyzed to date, and is consistent at different solar lines as well. This is shown in Figure 3, where mass density ratios are computed as a function of altitude are shown for 6 solar lines in the 50–70 nm range.

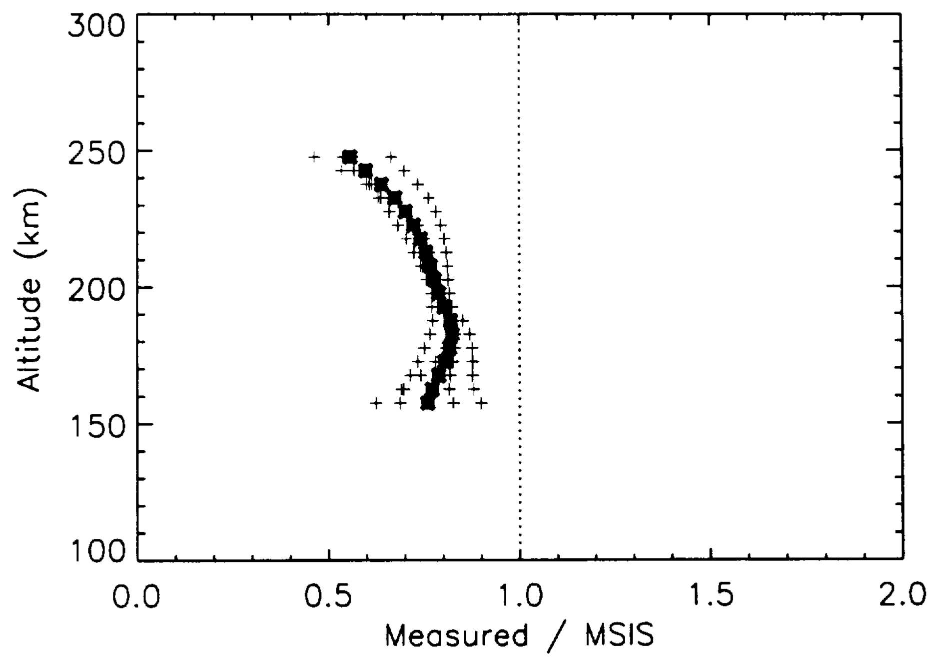


Figure 3. Mass density ratios from solar line attenuation data for 10/4/93.

This result demands further study, since although we expect that a semi-empirical climatological model such as MSIS will have significant deviation from a measurement at any particular place and time, measurement of systematically lower densities across differing levels of solar activity is disturbing.

## 5. Airglow Analysis

Airglow data were analyzed and compared to numerical model results generated using the measured solar spectrum, and a model atmosphere scaled according to solar line attenuation results described in section 4. A full description of the analysis and modeling techniques may be found in *Bailey* [1995]. A summary is presented here.

Altitude profiles of important emission lines and bands were extracted from the calibrated spectra. These are slant path column brightness measurements from the rocket location out to infinity at a local zenith angle of 90°. Thus, the airglow model is similarly integrated along the instrument line of sight. Model emission rate profiles are generated using the /glow electron transport model of S.C. Solomon, the Feutrier radiative transfer model of G.R. Gladstone, and the LBH band system model of S.M. Bailey. The solar line attenuation results are interpreted to indicate a linear factor decrease in the atomic oxygen density and no change in the molecular nitrogen density or exospheric temperature; this interpretation, although possibly ambiguous as described above, yields good agreement with airglow brightness measurements, as shown in Figure 4. $N_2$ LBH profiles for the (4,0) band at 132.5 nm and (2,0) band at 138.3 nm are in good agreement with the model when measured solar fluxes are used as the upper boundary condition. The bands are nearly equal at high altitude while the 138.3 nm profile exhibits attenuation due to absorption by $O_2$ at low altitude, in accord with model prediction. The OI $^5S$ doublet at 135.6 nm is only slightly optically thick and hence shows a high-altitude slope near the scale height of atomic oxygen, while the OI $^3S$ triplet at 130.4 nm is very optically thick and consequently a nearly flat altitude profile is observed. The combination of photoelectron and radiative transfer modeling does an excellent job of describing this profile.

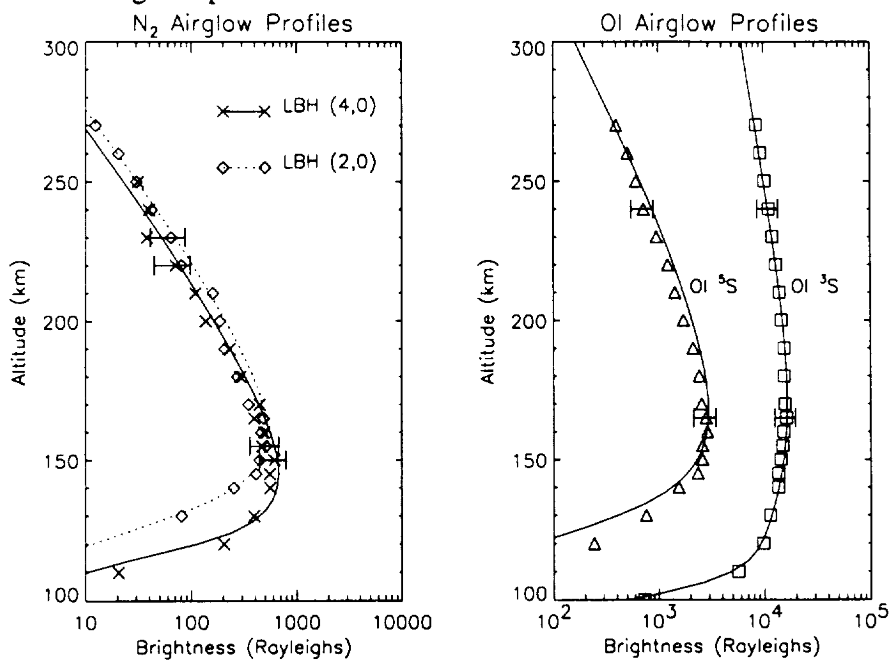


Figure 4. Measured (symbol) and modeled (line) airglow brightness profiles for 11/3/94

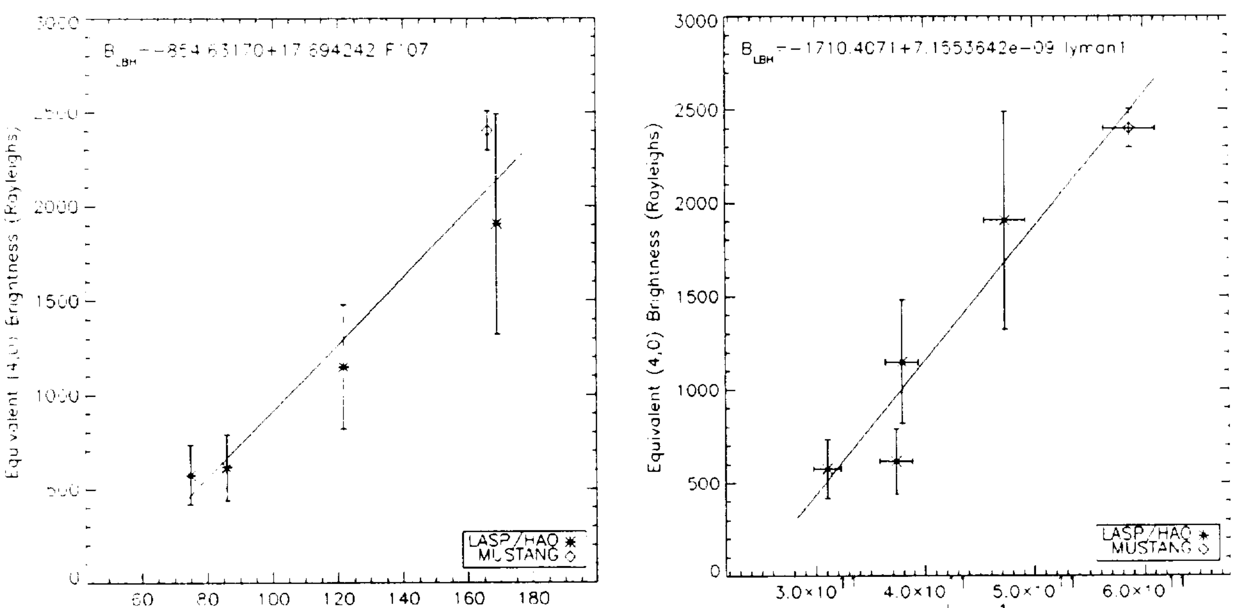


Figure 5. LBH (4,0) band peak brightnesses for the 4 rocket flights plotted against F10.7 and H Ly-a, both proxy indicators of the solar EUV flux. An additional point from an LBH measurement by the MUSTANG rocket, scaled to the (4,0) band, is also shown.

LBH peak brightnesses show a good correlation to standard indices of the solar EUV flux, as shown in Figure 5. The LBH (4,0) peak brightness is plotted against the $F_{10.7}$ index and the 121.6 nm HI Lyman-alpha solar flux measured by the UARS/SOLSTICE instrument. An additional point, obtained from the MUSTANG rocket flight in 1992 (D.D. Cleary, PI) is also included. This value was obtained from a spectral fit to several LBH bands in the 190-220 nm range, scaled to the (4,0) band using the LBH band system model.

An additional analysis of airglow data was performed on the NI 149.3 nm emission line. This line is prominent in the FUV spectrum and is a small but significant contributor to the band-integrated intensities measured by auroral and dayglow imagers such as the POLAR UVS instrument. Therefore, it is important to understand its excitation mechanisms. According to analysis of the Nov. 1994 flight data, the most important of these is photoelectron impact on $N_2$ resulting in dissociative excitation of N atoms, as shown in Figure 7. The LBH (3,3) band, which is blended with the 149.3 nm line, is also plotted as a contributor to the total measured brightness profile. Surprisingly, above ~250 km, photoelectron impact excitation of N atoms is the dominant source. Photodissociative excitation of $N_2$ was not found to be a significant contributor to the observed emission.

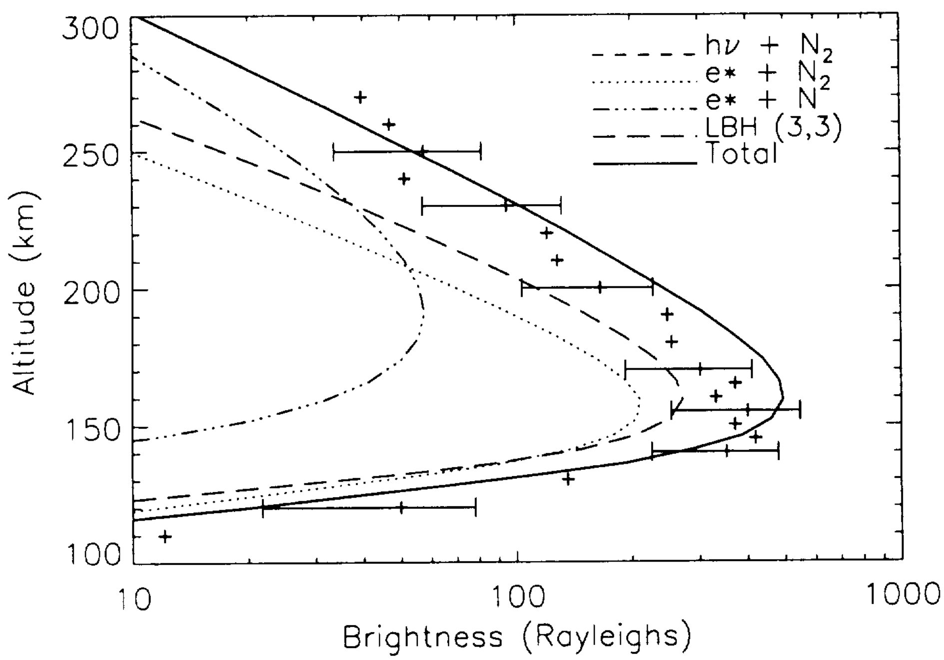


Figure 7. Measured (crosses) and modeled (lines) brightness profiles for the NI emission line at 149.3 nm. The contribution from the blended LBH (3,3) band is included.

## 6. Conclusion

The Solar Irradiance And Thermospheric Airglow Rocket Experiments have yielded important scientific results, as outlined above. More information can be found in the list of publications and conference papers supported in part by this grant, which is appended. In addition, the rocket flights have provided a vital test bed for development of instrumentation that will fly on the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) mission.

Two graduate students have been supported by this grant. Scott Bailey received the Ph.D. in 1995, and Steven Hill is expected to receive the Ph.D. in early 1999. Most of the research described above was performed by these graduate students, and is described in greater detail in their dissertations.

Additional information about the rocket flights, their results, data files, and related models may be found at the web site: *http://lasp.colorado.edu/rocket/*.

### Publications

Vacuum-Ultraviolet Instruments for Solar Irradiance and Thermospheric Airglow, T.N. Woods, G.J. Rottman, S. Bailey, and S.C. Solomon, *Opt. Eng.*, 33, 438, 1994.

Ionospheric Electron Densities Calculated Using Different EUV Flux Models and Cross Sections: Comparison with Radar Data, M.J. Buonsanto, P.G. Richards, W.K. Tobiska, S.C. Solomon, Y.K. Tung, and J.A. Fennelly, *J. Geophys. Res.*, *100*, 14569, 1995.

Response of the Upper Atmosphere to Variations in the Solar Soft X-ray Irradiance, S.M. Bailey, Ph.D. Dissertation, University of Colorado, 1995.

Calibration of the San Marco Airglow-Solar Spectrometer Instrument in the Extreme-Ultraviolet, J. Worden, T.N. Woods, G. Rottman, G. Schmidtke, H. Tai, H. Doll, and S.C. Solomon, *Opt. Eng.*, *35*, 554, 1996.

Solar Extreme Ultraviolet Irradiance Measurements during Solar Cycle 22, T.N. Woods, G.J. Rottman, S.M. Bailey, S.C. Solomon, and J.R. Worden, *Solar Physics*, 177, 133, 1998.

Real-Time, Single-Frame, Optimal Attitude Extimation Using Horizon Sensor and Magnetometer Data, S.M. Hill and T.J. McCusker, *J. Space. Rockets*, in press, 1998.

Sounding Rocket Measurements of the Solar Soft X-ray Irradiance, S.M. Bailey, T.N. Woods, L.R. Canfield, R. Korde, C.A. Barth, S.C. Solomon, and G.J. Rottman, *Solar Physics*, in press, 1998.

### Conference Papers

Recent Solar Vacuum Ultraviolet (VUV) Spectral Irradiance Measurements, T.N. Woods, G.J. Rottman, S.M. Bailey, and S.C. Solomon, American Geophysical Union spring meeting, 1994.

Simultaneous Measurements of the $N_2$ LBH Airglow and the Solar EUV and Soft X-ray Irradiance, S.M. Bailey, S.C. Solomon, and T.N. Woods, American Geophysical Union fall meeting, 1994.

Response of the FUV Dayglow to Solar and Thermospheric Variability, S.M. Bailey, S.C. Solomon, T.N. Woods, and G.R. Gladstone, IUGG XXI General Assembly, 1995.

Analysis of Rocket Observations of Far-Ultraviolet Atomic Oxygen Airglow, S.C. Solomon, S.M. Bailey, T.N. Woods, and G.R. Gladstone, American Geophysical Union fall meeting, 1995.

Simultaneous Observations of the NI 149.3 nm Emission and the Solar EUV Irradiance, S.M. Bailey, S.C. Solomon, and T.N. Woods, American Geophysical Union Fall Meeting, 1996.

The $N_2$ Triplet System, S.M. Hill and S.C. Solomon, American Geophysical Union Spring Meeting, 1997.

Thermospheric Neutral Composition Measured by Attenuation of Solar EUV Irradiance, S.M. Bailey, S.C. Solomon, and T.N. Woods, American Geophysical Union Fall Meeting, 1997.

Rocket Observations of $N_2$(LBH) Emissions in the Far-Ultraviolet Dayglow, S.M Hill, S.C. Solomon, S.M Bailey, T.N Woods, and D.D Cleary, American Geophysical Union Spring Meeting, 1998.