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INTERPRETATION OF NO AND OH EMISSION FROM 1976 AIRBORNE MEASURE--ETC(U)
JAN 79 J H SCHUMMERS, R J HUPPI F19628-78-C-0018

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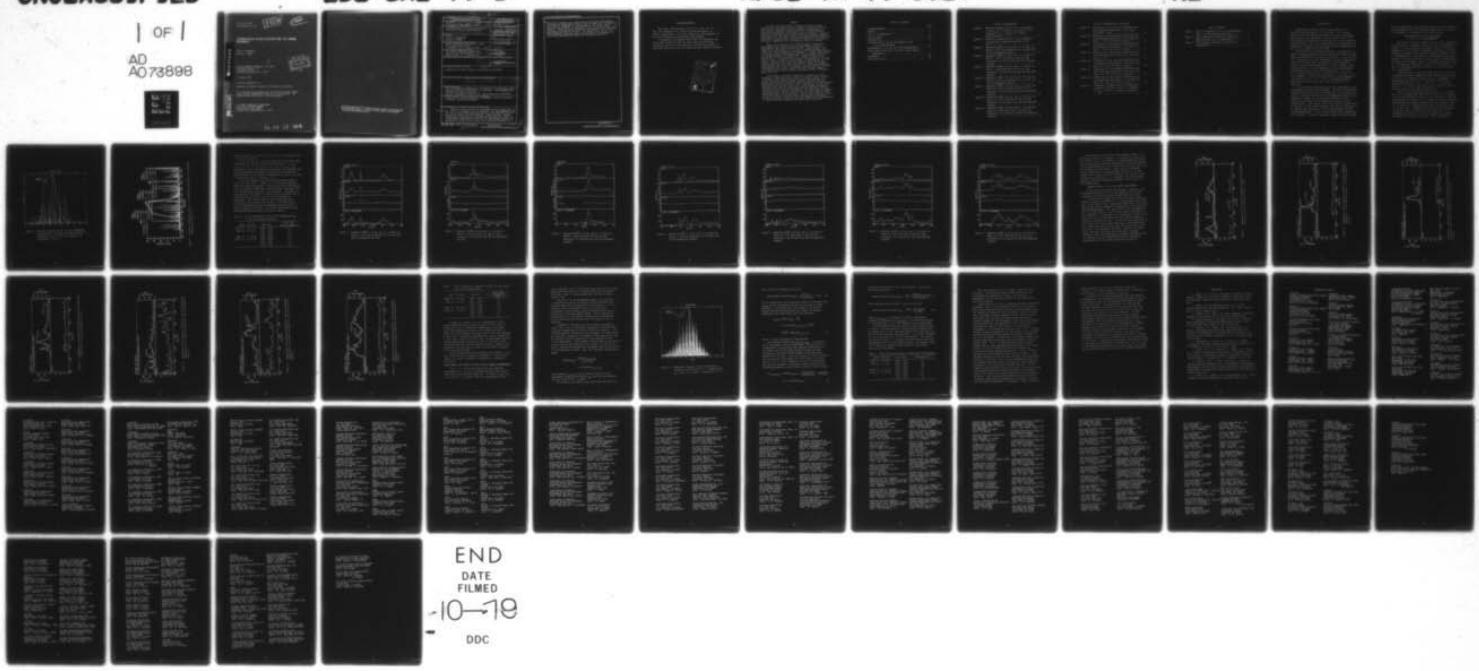

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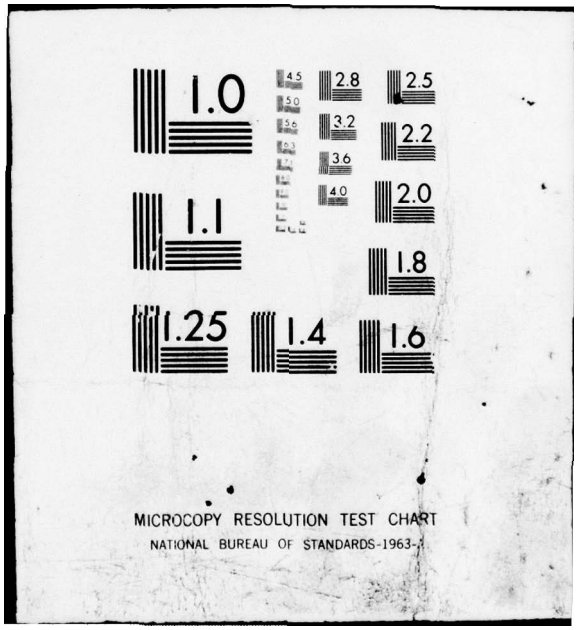
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HAES Report No. 80

LEVEL II

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INTERPRETATION OF NO AND OH EMISSION FROM 1976 AIRBORNE MEASUREMENTS

AD A073898

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1 January 1979

Scientific Report No. 1

This research was sponsored by the Defense Nuclear Agency under Subtask S99QZXHI004, Work Unit 11, entitled: IR Phenomenology and Optical Code Development.

AIR FORCE GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
HANSCOM AFB, MASSACHUSETTS 01731

(18) AFGL, DNA

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

(19) **REPORT DOCUMENTATION PAGE**

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFGL-TR-79-0027, HAES-80 (14)	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER: EDL-SRL-79-1	
4. TITLE (and Subtitle): (6) Interpretation of NO and OH Emission From 1976 Airborne Measurements	5. TYPE OF REPORT & PERIOD COVERED: Scientific Report No. 1
	6. PERFORMING ORG. REPORT NUMBER: HAES Report No. 80
7. AUTHOR(s): (10) John H. Schummers*, Ronald J. Huppi	8. CONTRACT OR GRANT NUMBER(s): (15) F19628-78-C-0018
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Electro-Dynamics Laboratories (SRL), Utah State University, 1 DeAngelo Drive, Bedford, Mass. 01730	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 767011AB
11. CONTROLLING OFFICE NAME AND ADDRESS: Air Force Geophysics Laboratory, Hanscom AFB, Massachusetts 01731, Monitor/Capt. R. P. Walker/OPR (11)	12. REPORT DATE: 1 Jan 1979
	13. NUMBER OF PAGES: 58
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): (12) 58 p.	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release, distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

(16) 7670, S99QZXHI (17) 11, I 004

18. SUPPLEMENTARY NOTES

This research was sponsored by the Defense Nuclear Agency under Subtask S99QZXHI004 Work Unit 11, entitled: IR Phenomenology and Optical Code Development.
*John H. Schummers is now at Air Force Geophysics Laboratory.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Nitric oxide, aurora, hydroxyl, radiometer, NKC-135 aircraft, infrared, auroral measurement.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Measured infrared emission enhancements and backgrounds in the 2.83 to 3.04 μm (micron) region are analyzed. The measurements used for the analyses were collected from the AFGL NKC-135A flying laboratory during the 1976 DNA/AFGL ICECAP program. Chemiluminescence from hydroxyl fundamental chemistry was found to be the major background emitter in the measurement region, and aurorally excited, nitric oxide first overtone chemistry is

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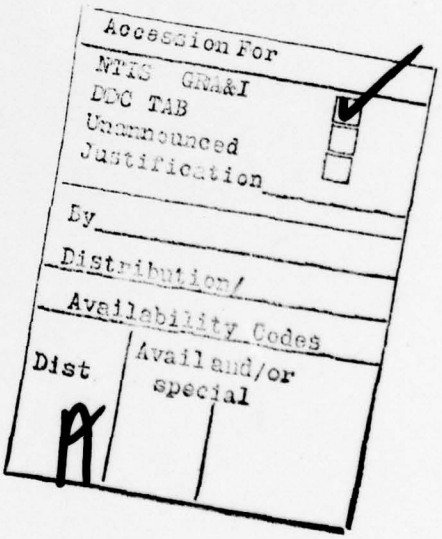
believed to account for large observed infrared enhancements. Assuming the enhancements result from NO chemistry, calculations were made to determine the percentage of the total auroral electron energy which is radiated as first overtone nitric oxide photons. The calculated percentage was found to vary from one measurement period to the next. It ranged from .4% to 1.0%, which probably indicates that the excitation is dependent on the auroral penetration depths and characteristics.

ACKNOWLEDGEMENTS

The support and guidance of Dr. A.T. Stair, Jr. of AFGL, who requested the analysis discussed herein, is greatly appreciated. Also, the support and encouragement of our DNA colleagues are gratefully acknowledged.

In addition, the authors would like to acknowledge and thank James Gibson of AFGL for generating and providing systematic spectra for the analysis, and Charles Eastman of Utah State University for his concerted data reduction efforts.



PREFACE

The High Altitude Effects Simulation (HAES) Program sponsored by the Defense Nuclear Agency since the early 1970 time period, comprises several groupings of separate, but interrelated technical activities, e.g., ICECAP (Infrared Chemistry Experiments--Coordinated Auroral Program). Each of the latter have the common objective of providing information ascertained as essential for the development and validation of predictive computer codes designed for use with high priority DOD radar, communications, and optical defensive systems.

Since the inception of the HAES Program, significant achievements and results have been described in reports published by DNA, participating service laboratories, and supportive organizations. In order to provide greater visibility for such information and enhance its timely applications, significant reports published since early calendar 1974 shall be identified with an assigned HAES serial number and the appropriate activity acronym (e.g., ICECAP) as part of the report title. A complete and current bibliography of all HAES reports issued prior to and subsequent to HAES Report No. 1, dated 5 February 1974 entitled, "Rocket Launch of an SWIR Spectrometer into an Aurora (ICECAP 72)", AFCRL Environmental Research Paper No. 466, is maintained and available on request from DASIAC, DOD Nuclear Information and Analysis Center, 816 State Street, Santa Barbara, California 93102, Telephone (805) 965-0551.

This report, Scientific Report No. 1 under Air Force Geophysics Laboratory (AFGL, formerly AFCRL) contract F19628-78-C-0018 is the eightieth report in the HAES series, and covers a portion of the ICECAP airborne technical efforts performed by the AFGL Infrared Flying Laboratory during February-March 1975 and February-March 1976. The purpose of the work reported herein was to investigate high altitude atmospheric infrared emissions from the spatially and temporally varying locations of the NKC-135A platform at the same times as intense auroral sampling efforts from ground and rocket-borne ICECAP experiments were being performed. Thus, a cost effective state of the art probe of selected infrared radiations was made to provide bench mark radiance level measurements for determination of future spectral scanning instrument specifications.

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INTRODUCTION

Significant infrared emission enhancements in a spectral band centered at 2.94 μm (2.84 - 3.04 μm) were measured from the AFGL flying laboratory with a radiometer while viewing the atmosphere, *Huppi and Reed* [1977]. The measurements were made as part of the 1975 and 1976 DNA/AFGL ICECAP program. The 2.94 μm enhancements are spatially and temporally correlated with aurorally induced enhancements of the N_2^+ first negative band at 3914Å.

The measured 2.94 μm enhancements are superimposed on a slowly varying background emission which even exists at times when the atmosphere is not excited by aurora. *Huppi and Reed* [1977] postulate that this background is mainly chemiluminescence from hydroxyl (OH) fundamental airglow chemistry. However, this OH chemiluminescence is not a feasable source of the measured 2.94 μm enhancements, since corresponding enhancements are not seen in the OH overtone (5, 3) and (6, 4) bands as monitors by a coaligned 1.7 μm (1.66 - 1.74 μm) radiometer. A more feasible source of the enhancements postulated by *Stair et al.* [1975], is chemiluminescence generated by nitric oxide (NO) first overtone ($\Delta V = 2$) chemistry.

In this report investigations of the background and the enhancement emissions are performed. The first section gives consideration to the source producing the slow varying background. Calculations show that OH fundamental emissions can completely account for the measured background levels. A method for removing the OH background is applied to the measured data. The results verify the calculated predictions of the OH, and they allow magnitude and time correlations to be readily made between the 2.94 μm enhancements and the 3914Å enhancements. In the second section these comparisons are discussed. Using the magnitude comparisons and assuming

that the enhancements are chemiluminescence from NO chemistry, the percentage of the total auroral energy which is emitted as NO photons is calculated in the final section.

CONSIDERATION OF THE OH BACKGROUND IN THE 2.94 μm MEASUREMENTS

The relative spectral response of the 2.94 μm radiometer is overlayed on a synthetic spectrum of the OH fundamental in Figure 1. That spectrum was calculated using a rotational temperature of 220°K and a vibrational temperature of 5000°K. Likewise, in Figure 2 the relative spectral response of the 1.7 μm radiometer is overlayed on an OH overtone spectrum as measured by *Steed* [1978] with a field widened interferometer. As shown in the figures, the 1.7 μm channel sees most of the (5, 3) transitions and part of the (6, 4) transitions, while the 2.9 μm channel sees parts of the (1, 0), (2, 1), and (3, 2) transitions.

A more specific inspection shows that the (5, 3) P and Q branches are almost completely seen, and about 50 percent of the (6, 4) R branch is seen by the 1.7 μm channel. If one assumes that for the $\Delta V = 2$ sequence, the relative emission ratios are P : R : Q = 38 : 22 : 2 as given by *Kofsky et al.* [1975], then 65 percent of the (5, 3) and 18 percent of the (6, 4) bands are observed.

The 2.94 μm channel sees most of the (1, 0) P branch, and (2, 1) Q branch, and about half of the (1, 0) Q branch, (2, 1) P and R branches, and the (3, 2) R branch. From the measurements of *MacDonald et al.* [1968], or from a synthetic spectrum one can roughly calculate that 60 percent of the (1, 0) and (2, 1) transitions and about 10 percent of the (3, 2) are seen. A LOWTRAN calculation of the atmospheric absorption shows that both the 2.9 μm and the 1.7 μm passbands are relatively free of atmospheric absorption problems at the aircraft altitude. Thus, atmospheric

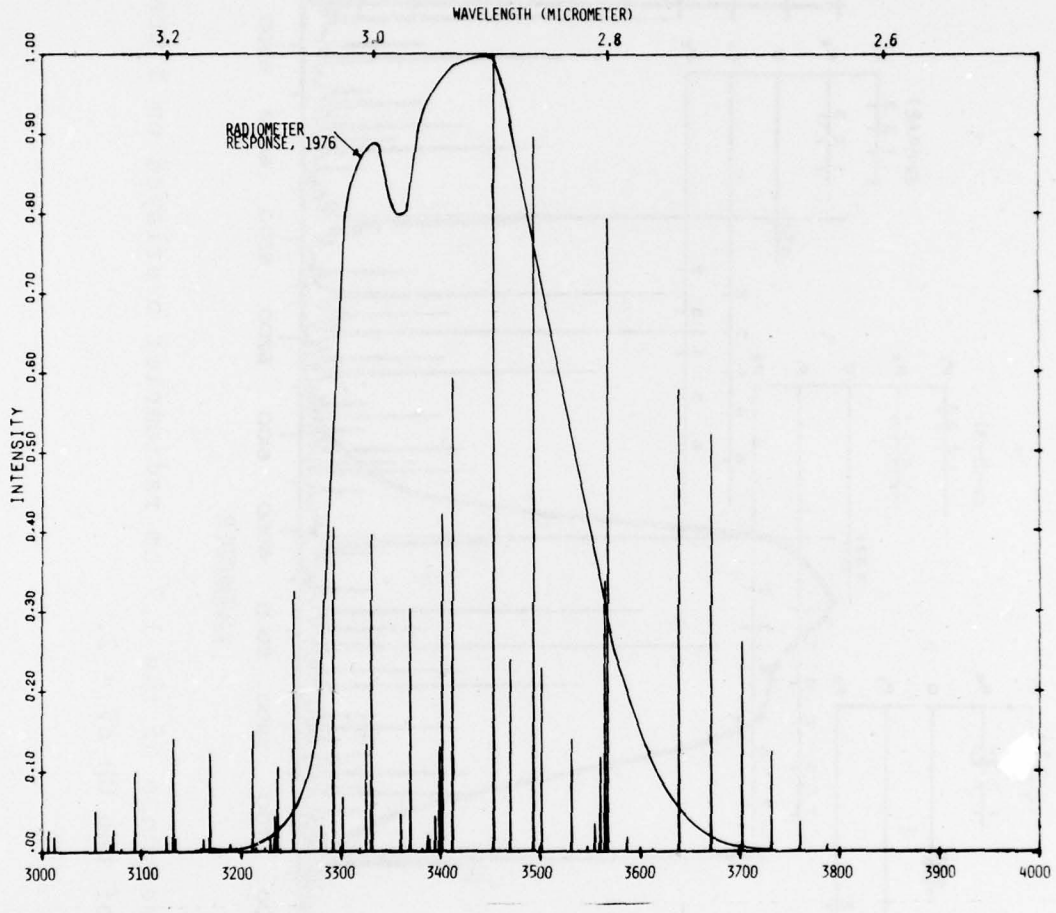

Figure 1. Relative response of the 2.94 μm radiometer overlayed on a synthetic spectrum of OH $\Delta V = 1$, computed for $T_R = 220^{\circ}K$, $T_V = 5000^{\circ}K$, and resolution = 1 cm^{-1}.

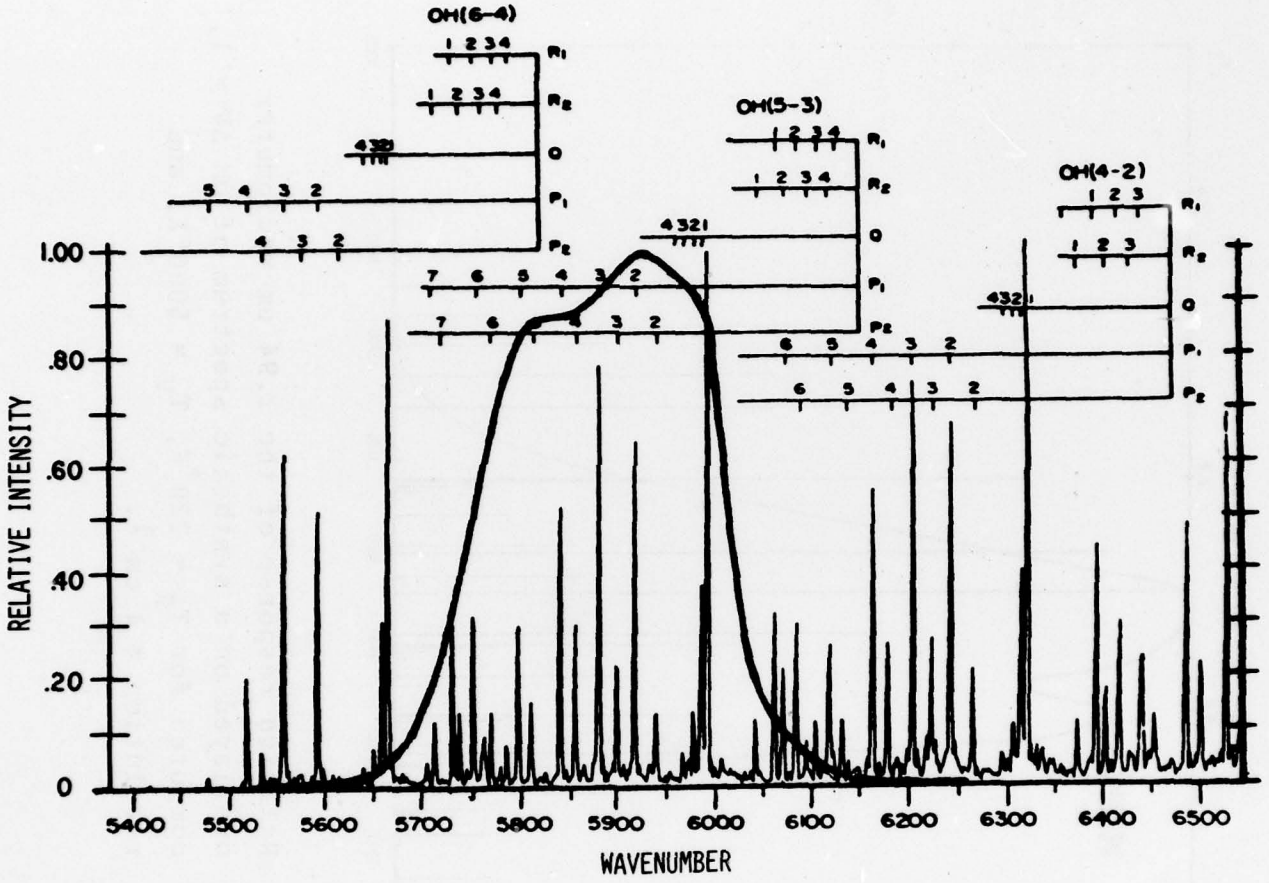

Figure 2. Relative response of the 1.7 μm radiometer overlayed on a measured spectrum of the OH $\Delta V = 2$.

absorption has no significant effect on the percentages seen of the various bands.

Baker [1976] gives the following relative emission band intensities for the OH overtone and fundamental: (1, 0): (2, 1): (3, 2): (5, 3): (6, 4) = 76 : 40 : 18 : 40 : 39. Using these ratios and applying the portion of each band seen in the measurement passband as given above, the expected observed ratio of the hydroxyl fundamental in the 2.9 μm band to overtone in the 1.7 μm band is 2.2.

Let's now compare this with the measurements made by *Huppi and Reed* [1977]. Figures 3 to 9 show the measured data for seven time periods. From top to bottom the figures give the measured 3914Å (N_2^+) auroral monitor emissions, the 2.94 μm emissions, and the 1.7 μm emissions. Included at the bottom of the figure is a plot of the remaining 2.94 μm emission after a ratio of the 1.7 μm OH overtone is subtracted. The ratios used for the subtraction were selected to give the best fit of the 1.7 μm data to the 2.94 μm backgrounds which were measured during times of minimal auroral excitation. The ratios determined for the seven measurement periods are given in Table 1.

Table 1. Ratios of Measured 2.94 μm, OH Fundamental and 1.7 μm OH Overtone Emissions

Date - Mission	Time (UT)	Ratio (kR) OH(2.9μ)/OH(1.7μ)
3 Mar 76 - IC 76 -6	0500 - 0530	1.7
7 Mar 76 - IC 76-9	1000 - 1030	1.7
	1120 - 1150	1.6
8 Mar 76 - IC 76-10	0730 - 0800	1.7
20 Mar 76 - IC 76-16	0905 - 0935	2.1
	1010 - 1040	2.1
	1120 - 1150	2.1

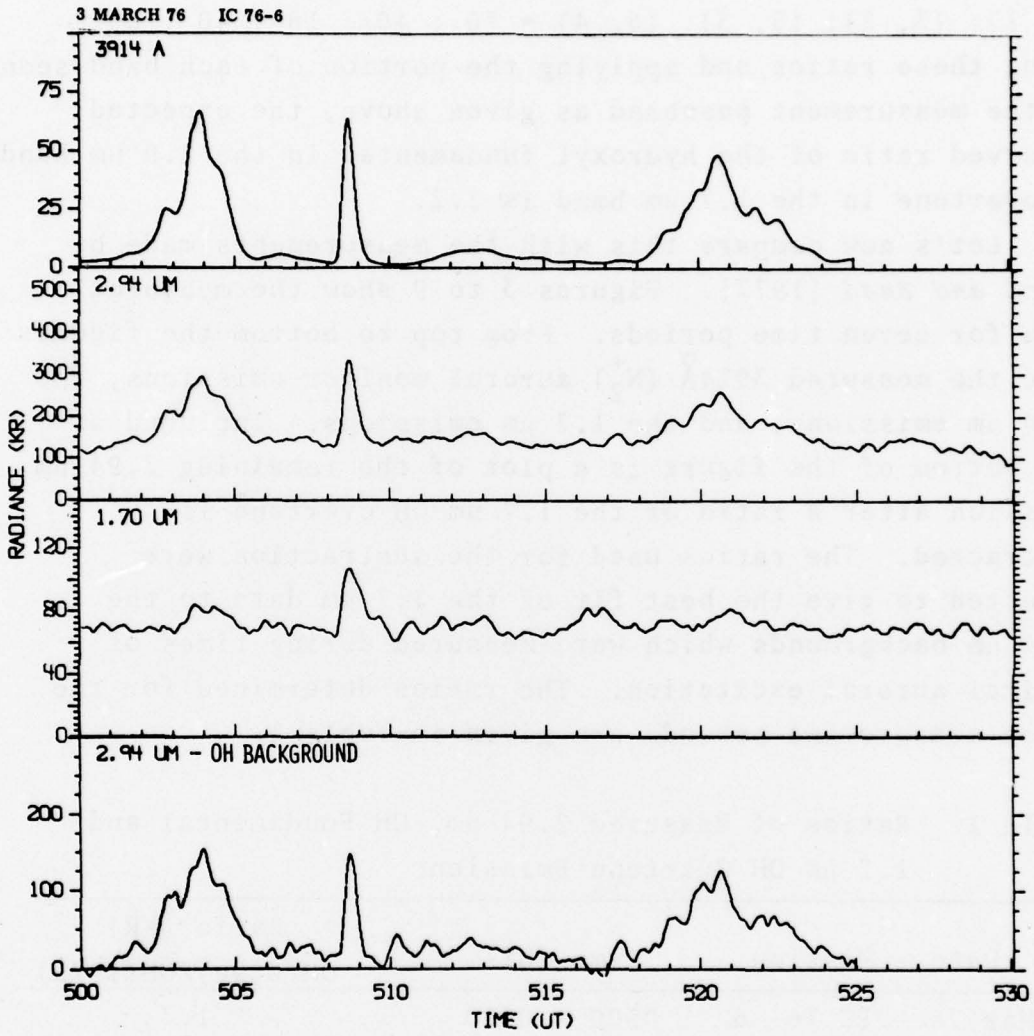

Figure 3. Measured 3914Å, 2.94 μm, and 1.7 μm data for March 3, 1976 and processed 2.94 μm data with the OH background removed.

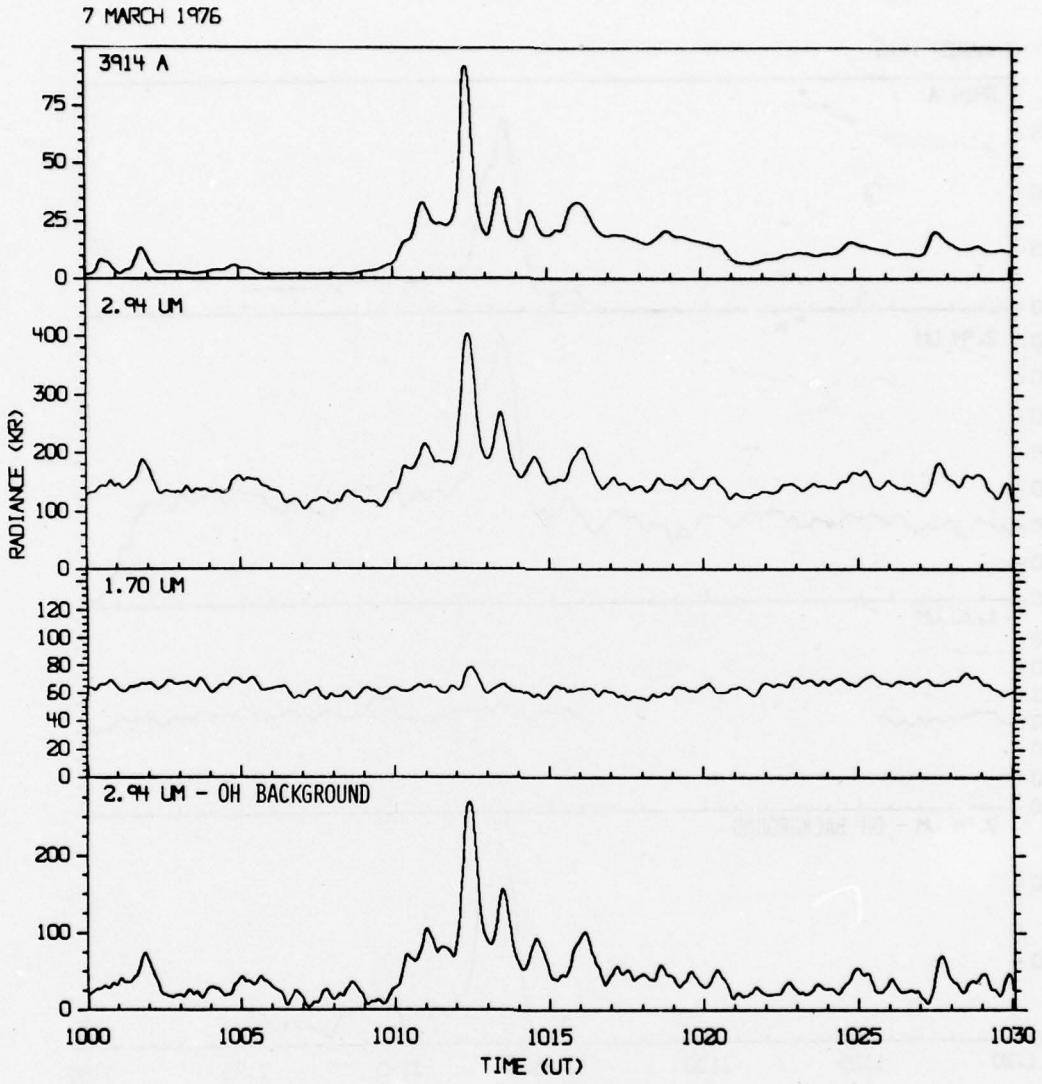

Figure 4. Measured 3914Å 2.94 μm, and 1.7 μm data for March 7, 1976 from 1000 to 1030 UT, and processed 2.94 μm data with the OH background removed.

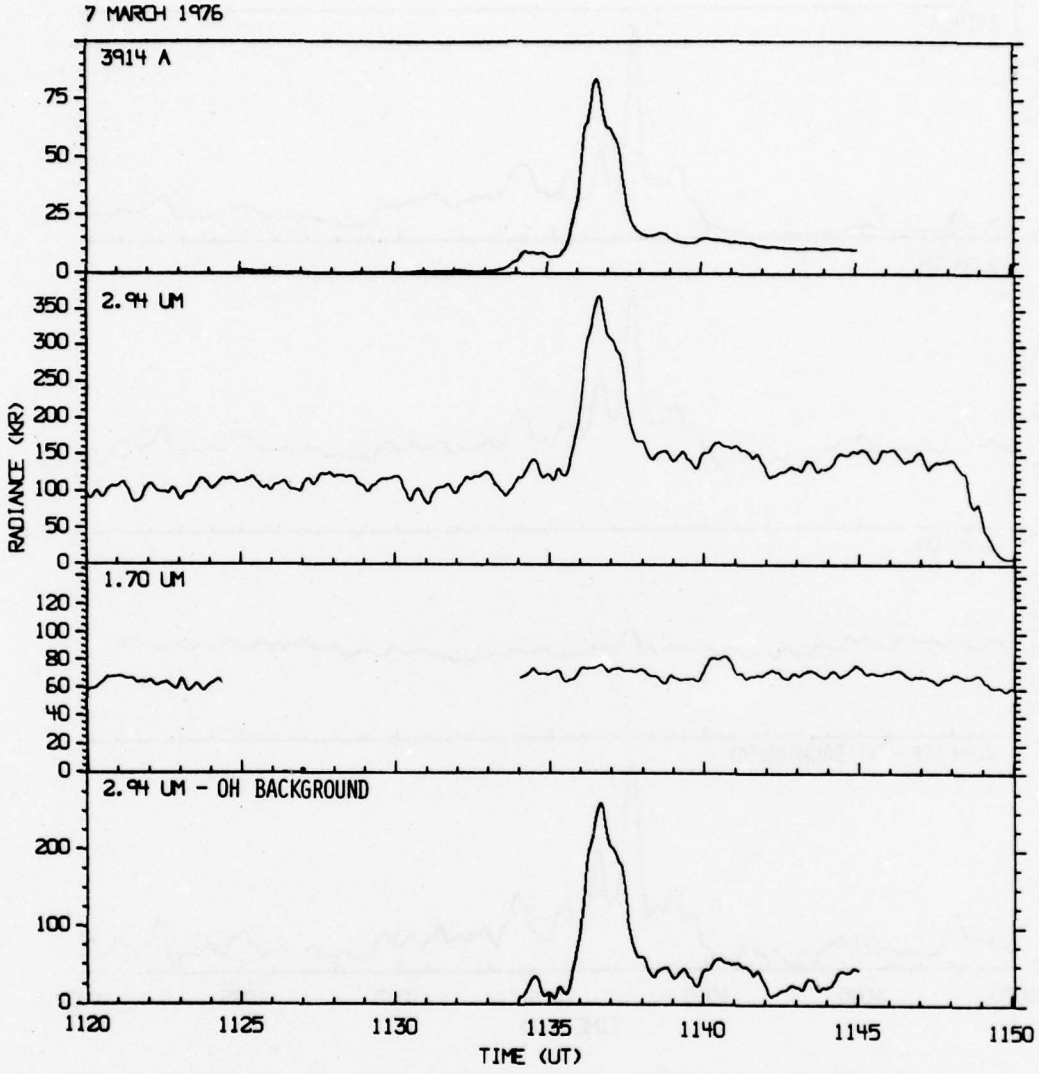

Figure 5. Measured 3914Å, 2.94 μm, and 1.7 μm data for March 7, 1976 from 1120 to 1150 UT, and processed 2.94 μm data with the OH background removed.

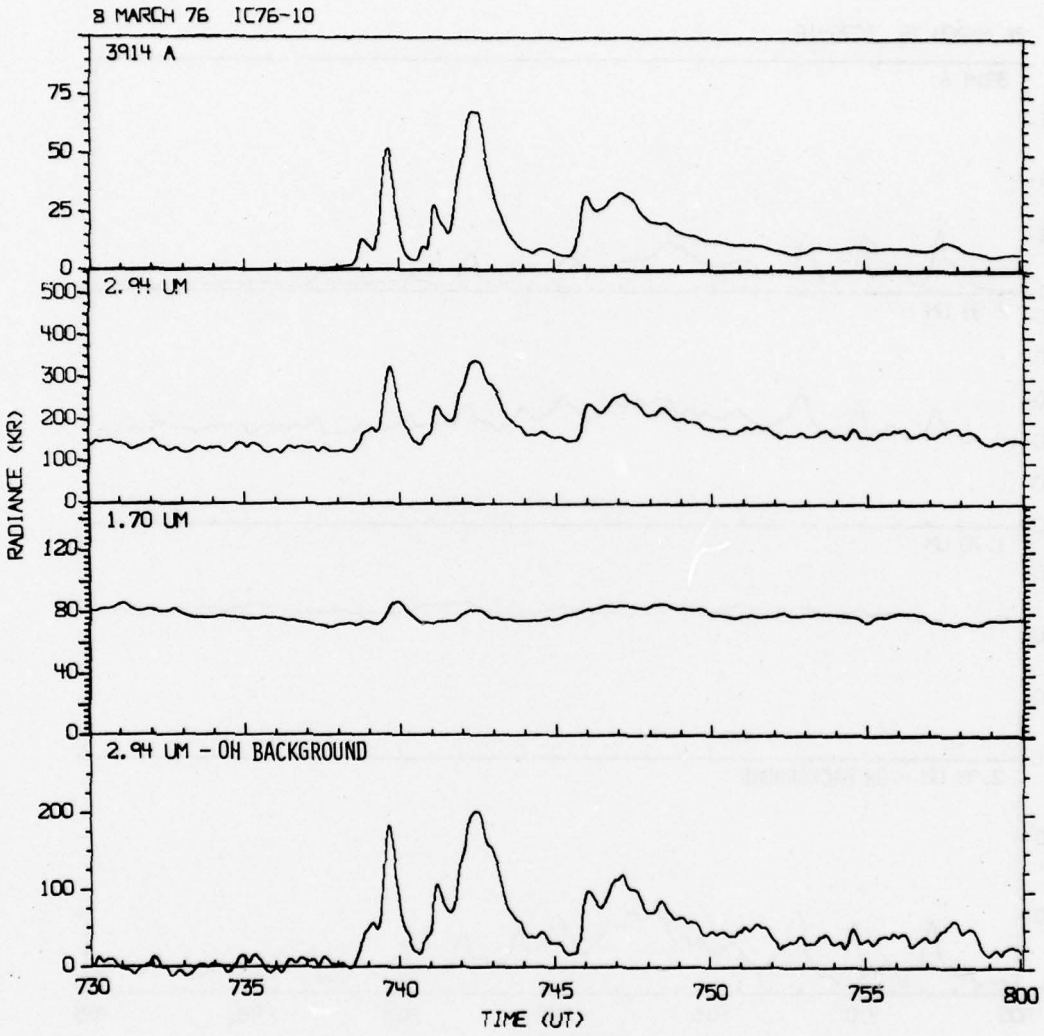

Figure 6. Measured 3914Å, 2.94 μm, and 1.7 μm data for March 8, 1976 and processed 2.94 μm data with the OH background removed.

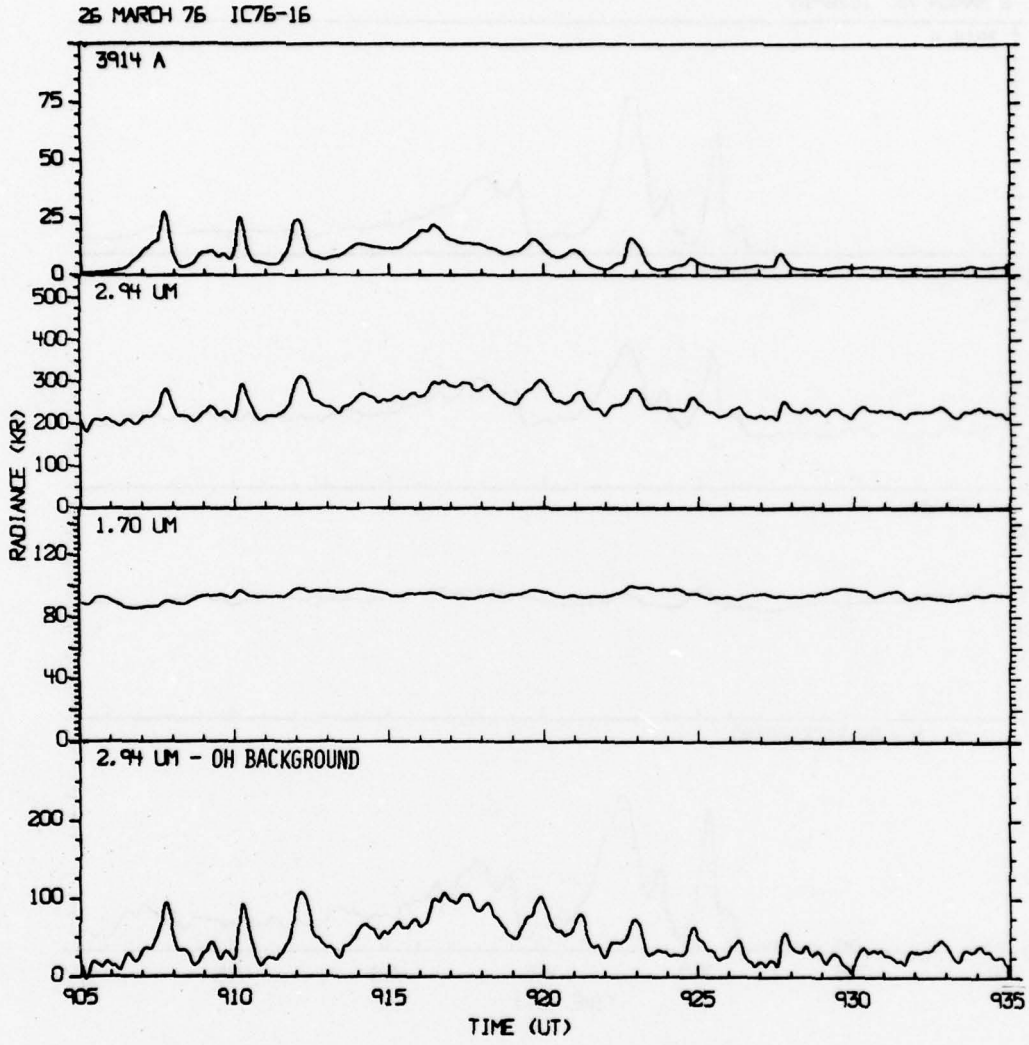

Figure 7. Measured 3914Å, 2.94 μm, and 1.7 μm data for March 26, 1976 from 0905 to 0935 UT, and processed 2.94 μm data with the OH background removed.

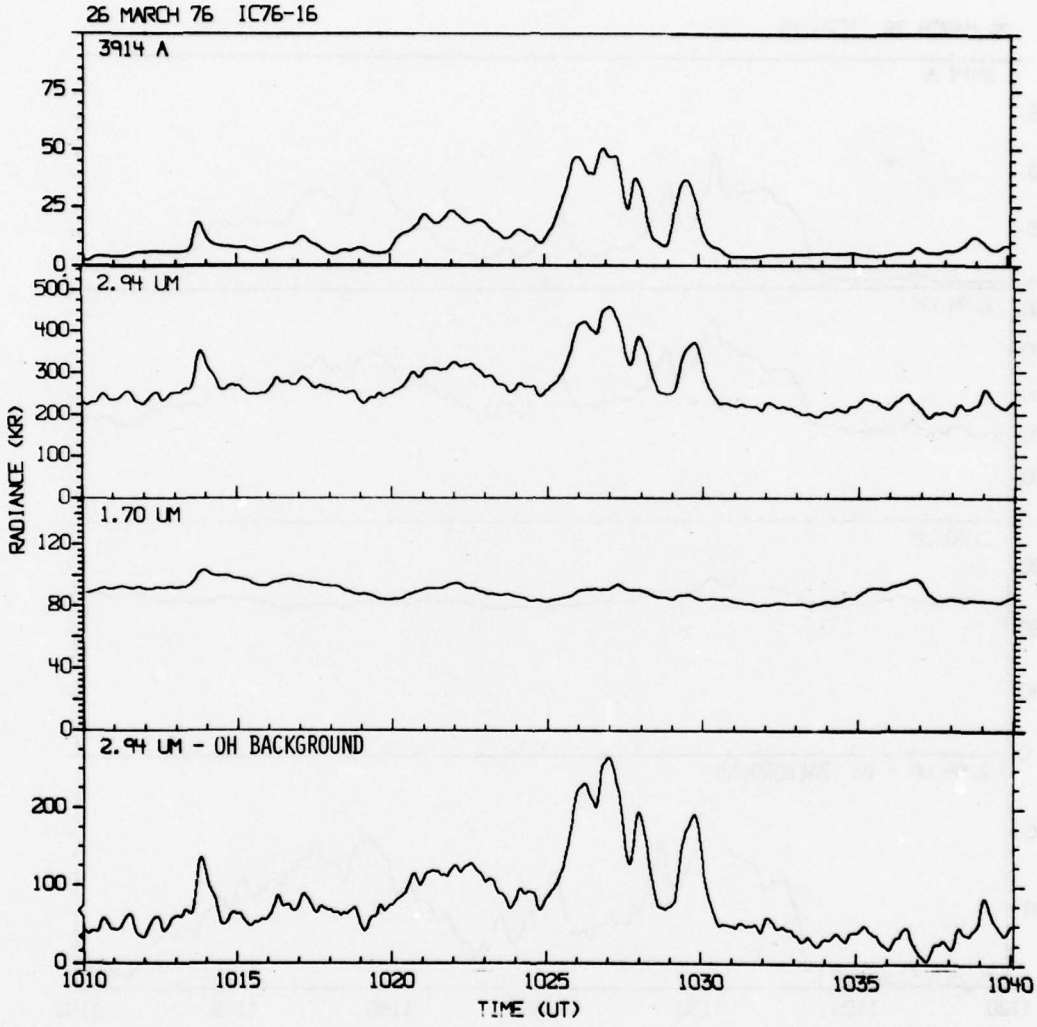

Figure 8. Measured 3914Å, 2.94 μm, and 1.7 μm data for March 26, 1976 from 1010 to 1040 UT, and processed 2.94 μm data with the OH background removed.

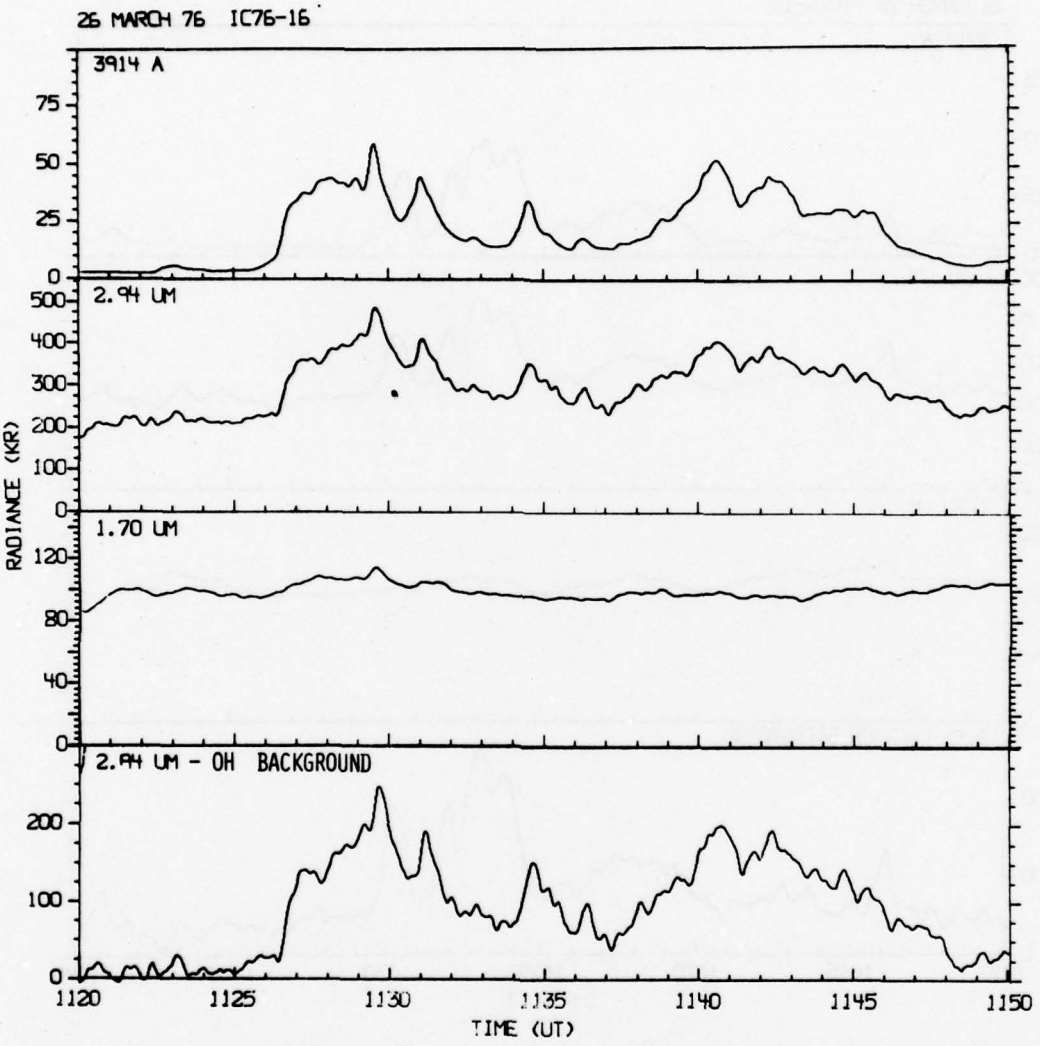

Figure 9. Measured 3914Å, 2.94 μm, and 1.7 μm data for March 26, 1978 from 1120 to 1150 UT, and processed 2.94 μm data with the OH background removed.

The ratios are very close to the expected value of 2.2 which was previously calculated. As discussed by *Huppi and Reed* [1977], the 1.7 μm channel is a good monitor of the OH even during periods when the atmosphere is excited by aurora since contaminations within the passband from other emissions are minimal and predictable. Thus, since the measured ratios between the 2.9 μm background and the 1.7 μm data compare very closely with the predicted ratio based on the OH analysis given above, it is apparent that the OH fundamental is the prime background radiator in the 2.94 μm measurement band.

COMPARISONS OF 2.94 μm AND 3914Å ENHANCEMENTS

As can be seen by inspecting Figures 3 through 9, the background-subtracted 2.94 μm data appears to be closely correlated with the relatively prompt 3914Å (N_2^+) data.

A more detailed comparison of the two sets of data is shown in Figures 10 through 16. In these figures the 3914Å data is overlayed on the background-subtracted 2.94 μm data, thus giving time and magnitude comparisons of the aurorally induced enhancements. The scale on the left corresponds to the 2.9 μm data and the scale on the right corresponds to the 3914Å data. To determine the correlation, a plot of the ratio of the 2.94 μm radiation to the 3914Å radiation is shown as a function of time. It was not always possible to get a flat ratio curve indicating close correlation since the signal-to-noise ratio was poor for levels under 25 to 50 kR of 2.94 μm enhanced radiation. However, for levels higher than this the ratio was quite flat, although different times and enhancements produced different ratios. The average ratio was determined for each time period investigated and the results tabulated in Table 2.

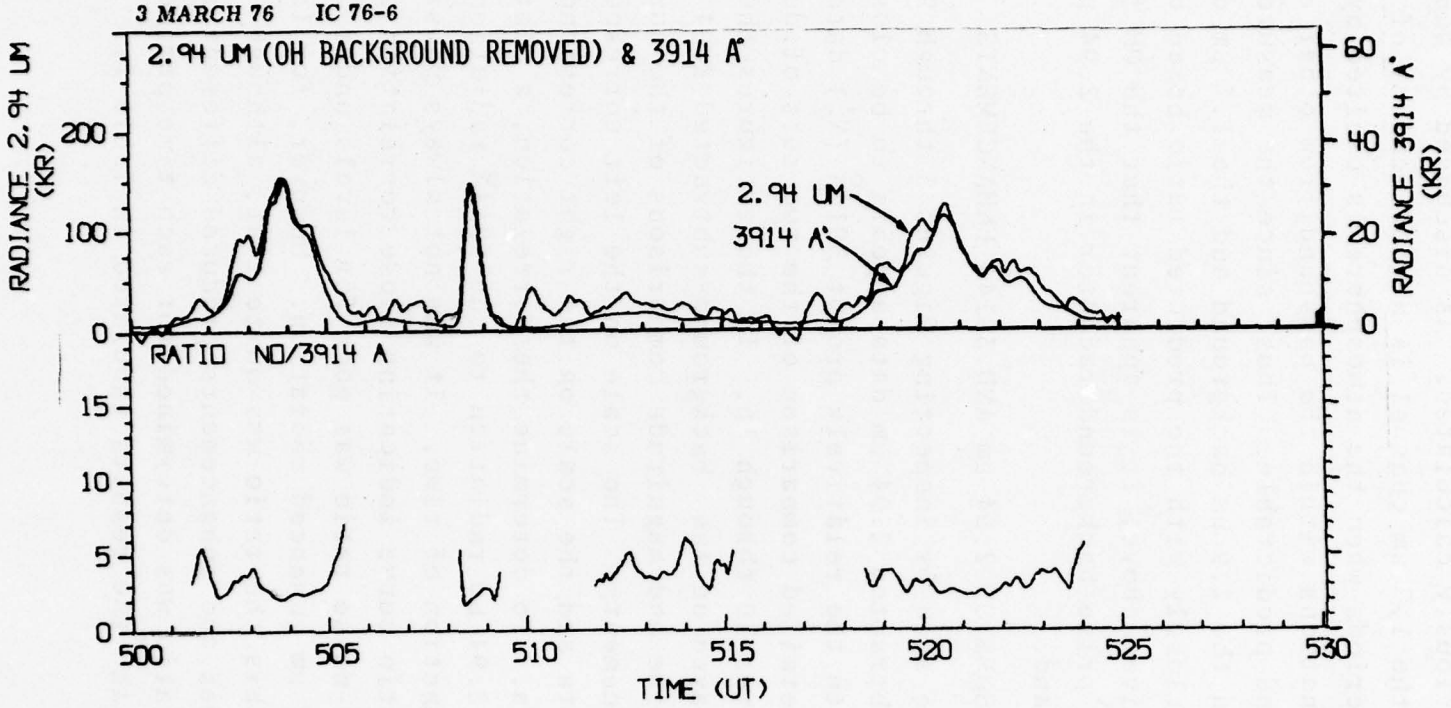

Figure 10. Comparison of the measured 3914Å data and the background-subtracted 2.94 μm data for March 3, 1976.

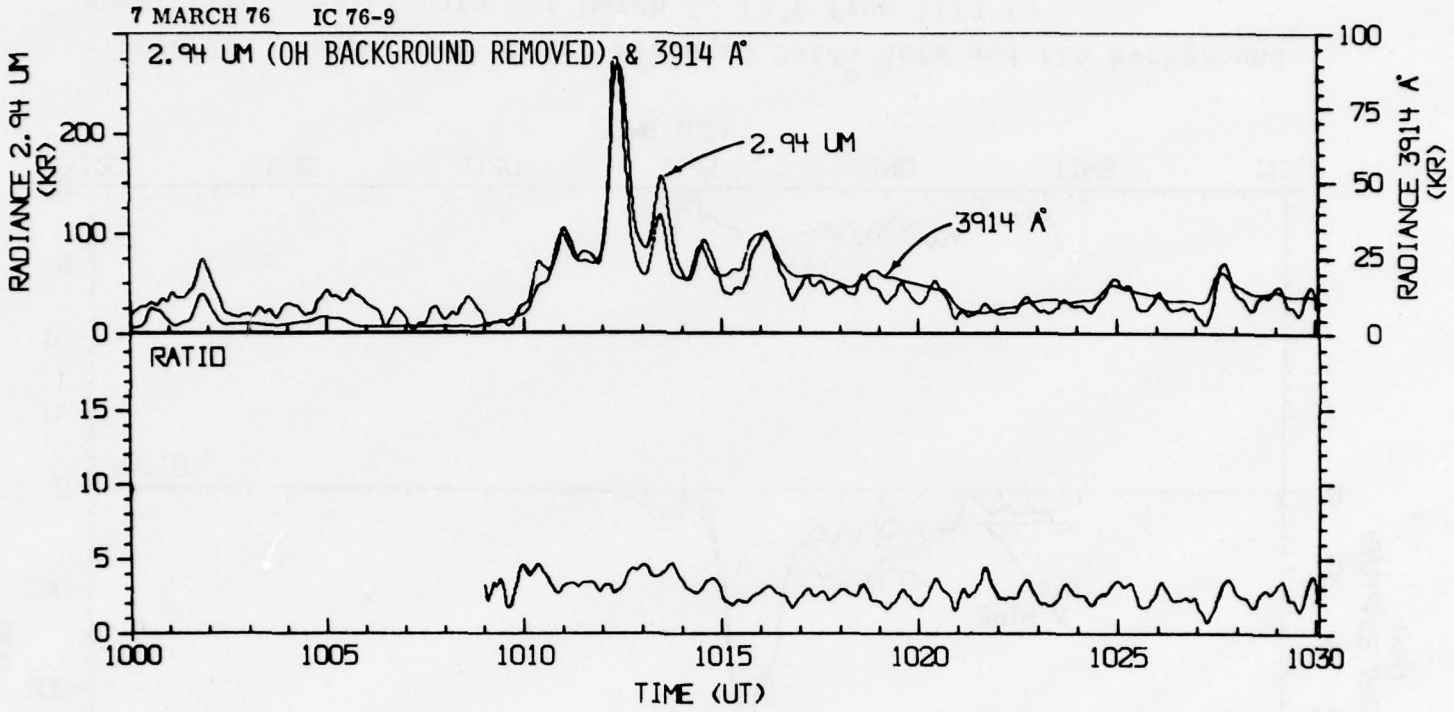

Figure 11. Comparison of the measured 3914Å data and the background-subtracted 2.94 μm data for March 7, 1976 from 1000 to 1030 UT.

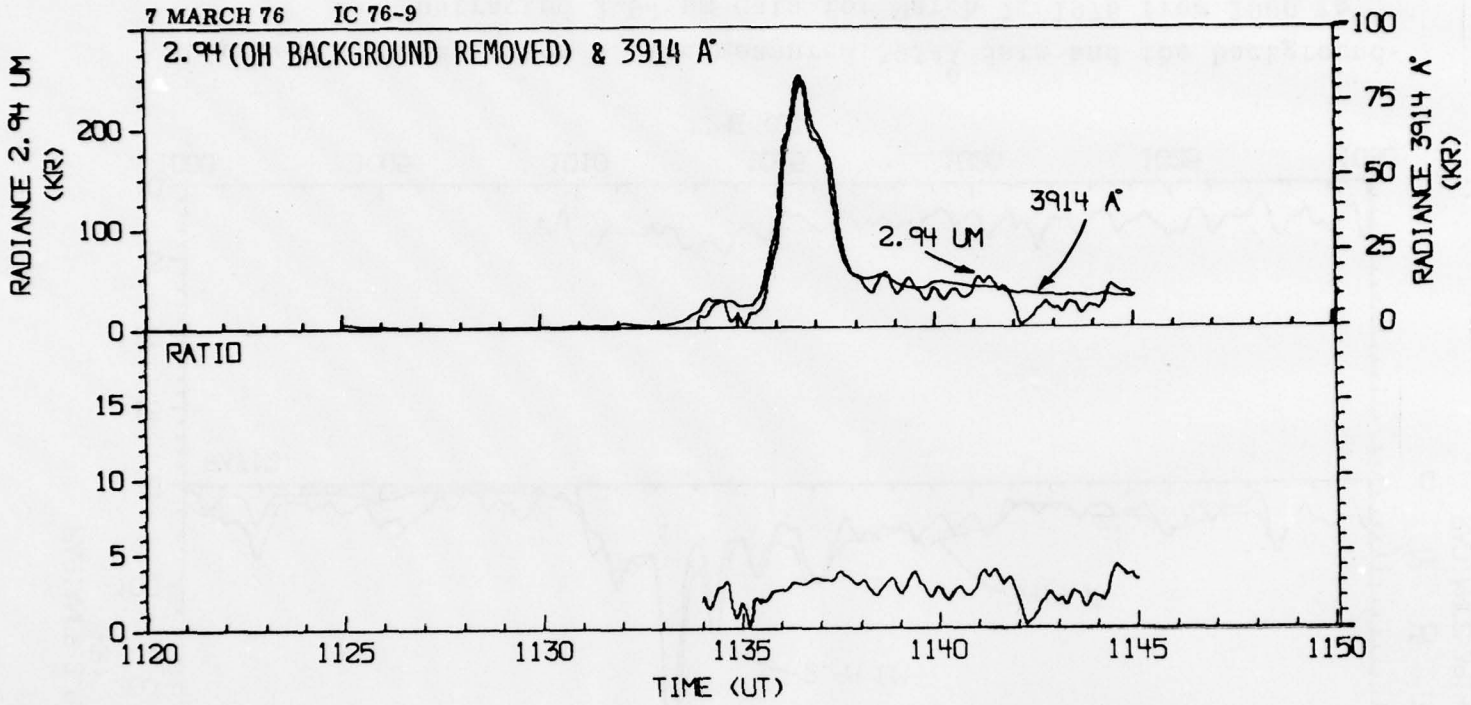

Figure 12. Comparison of the measured 3914Å data and the background-subtracted 2.94 μm data for March 7, 1976 from 1120 to 1150 UT.

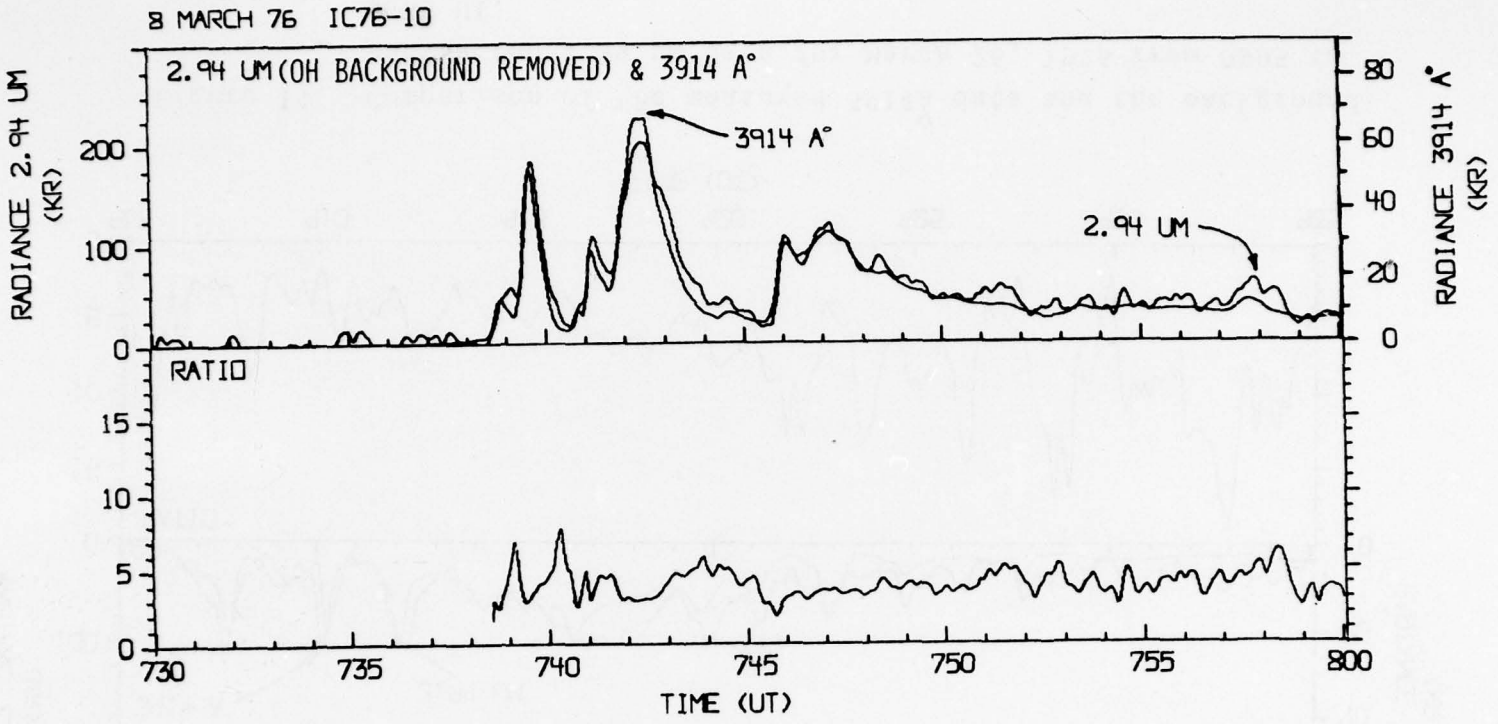

Figure 13. Comparison of the measured 3914Å data and the background-subtracted 2.94 μm data for March 8, 1976.

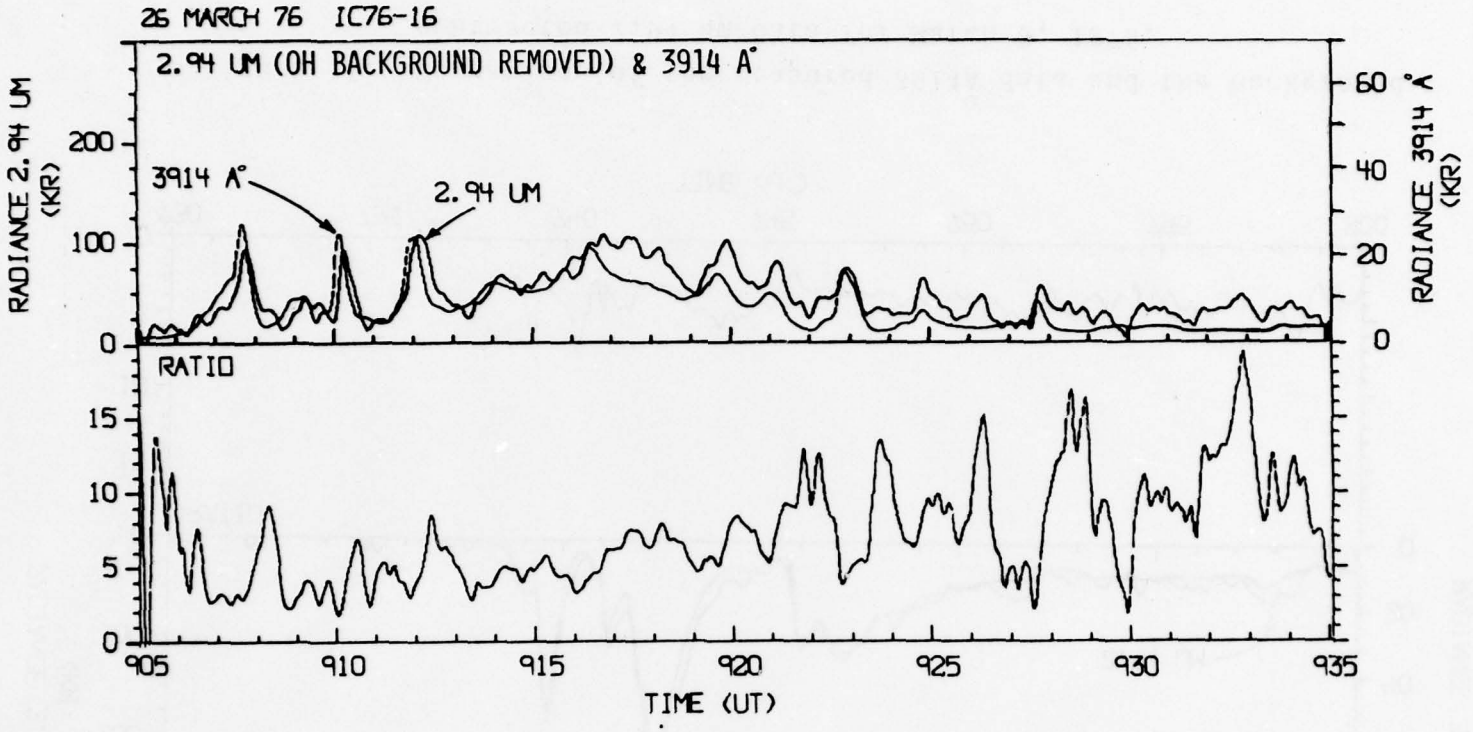

Figure 14. Comparison of the measured 3914Å data and the background-subtracted 2.94 μm data for March 26, 1976 from 0905 to 0935 UT.

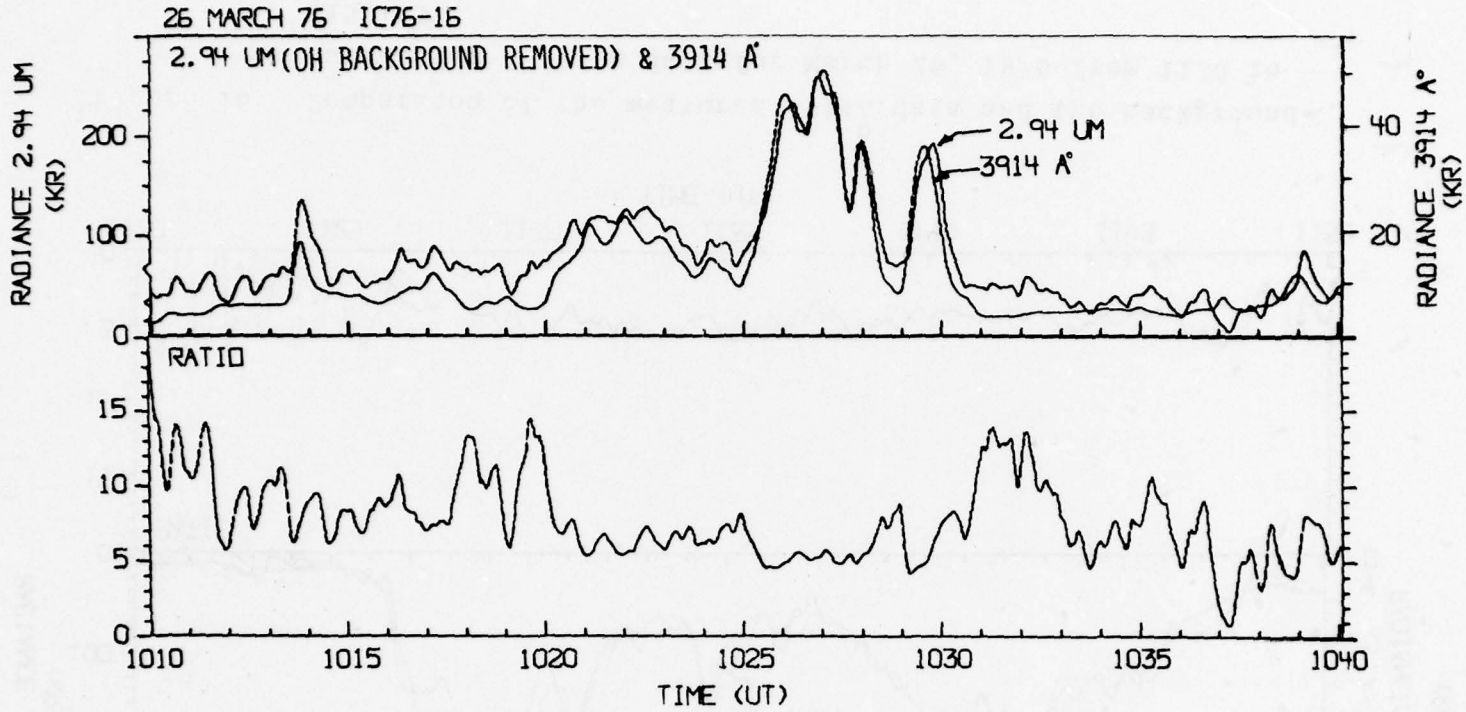

Figure 15. Comparison of the measured 3914Å data and the background-subtracted 2.94 μm data for March 26, 1976 from 1010 to 1040 UT.

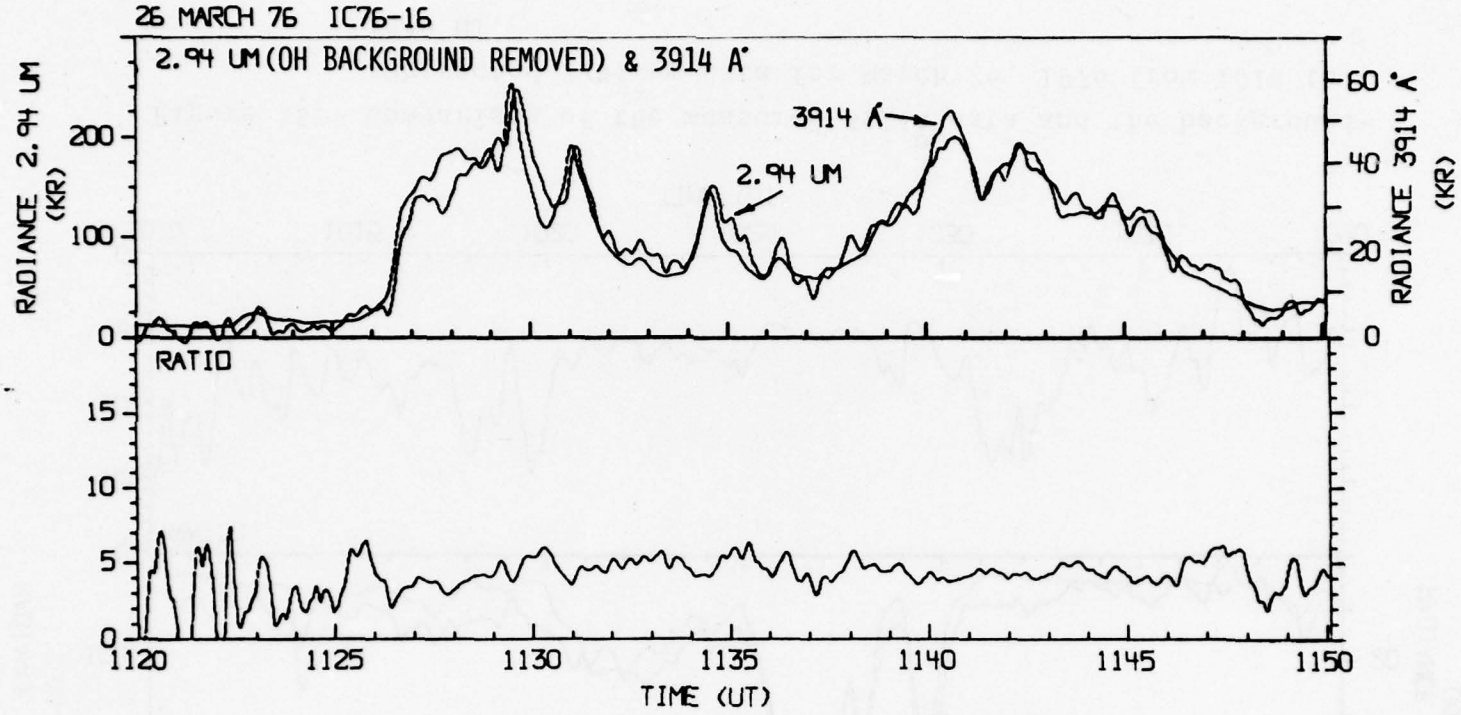

Figure 16. Comparison of the measured 3914Å data and the background-subtracted 2.94 μm data for March 26, 1976 from 1120 to 1150 UT.

Table 2. Ratio Comparison of Measured 3914Å (N_2^+) Emissions and 2.94 μm Enhancements

Date - Mission	Time (UT)	Ratio (kR) 2.94 μm Enhancement/ 3914Å
3 Mar 76 - IC 76-6	0500 - 0530	2.3
7 Mar 76 - IC 76-9	1000 - 1030	3.0
	1120 - 1150	3.0
8 Mar 76 - IC 76-10	0730 - 0800	3.3
26 Mar 76 - IC 76-16	0905 - 0935	4.3
	1010 - 1040	5.2
	1120 - 1150	4.3

As shown in Figures 10 to 16, enhancements of the scaled 3914Å data curve compare closely in time with the enhancements of the background subtracted 2.94 μm data. Since the enhancement process of the 3914Å emissions is known to be very prompt, one might surmise that the response of the 2.94 μm radiation enhancements to auroral deposition is also fast. Exactly how fast can't be determined from the present measurements because the data is limited by time filtering which was used to reduce the noise. However, the generation time and half life must be less than 15 seconds to fit the measured data.

There are some time shifts between the 3914Å and 2.94 μm data in the curves of Figures 14 through 16. These shifts appear to be real, although no explanation is presently available.

PHOTO-ENERGY EFFICIENCY OF NITRIC OXIDE AURORAL ENHANCEMENTS

Stair et al. [1975] postulated that the measured enhancements at 2.94 μm are chemiluminescence from nitric oxide (NO) first overtone chemistry. As shown by *Huppi and Reed* [1977], it is unlikely that the enhancements could

result from H_2O, CO_2 or OH emissions which are the only other known emissions which are of significance near the measurement band. Thus, it would appear that the only probable source is NO.

Since the 2.94 μm enhancements appear to be directly correlated with auroral excitation of the atmosphere and assuming that they are generated by NO chemistry, it is of interest to use the measured data to calculate the percentage of the incoming auroral electron energy that is emitted as NO overtone photon energy. Before making the calculation it is necessary to determine the relationship between the emitted NO photons and the measured 2.94 μm emissions.

A synthetic spectrum of the NO overtone generated by *Gibson* [1977] for a vibrational temperature of 5000°K and a rotational temperature of 220°K is shown in Figure 17. The relative spectral response of the radiometer is overlayed on the spectrum. Using this information Gibson calculates that 40 percent of the NO overtone is in the passband of the 2.9 μm measurement. Using LOWTRAN calculations for an arctic winter, one can determine that 96.5 percent of this 40 percent is transmitted through the atmosphere from 100 km to the 10.5 km aircraft altitude. Thus, the following relationship holds:

$$\text{Photons}_{(NO)} = \frac{\text{Photons}_{(2.94\ \mu m)}}{.40 \times .965}$$

$$= 2.59\ \text{Photons}_{(2.94\ \mu m)} \qquad (1)$$

where $\text{Photons}_{(2.94\ \mu m)}$ are the photons emitted in the measurement passband and $\text{Photons}_{(NO)}$ are the total photons emitted in the NO $\Delta V = 2$ bands.

To calculate the photo-energy efficiency of the NO, we

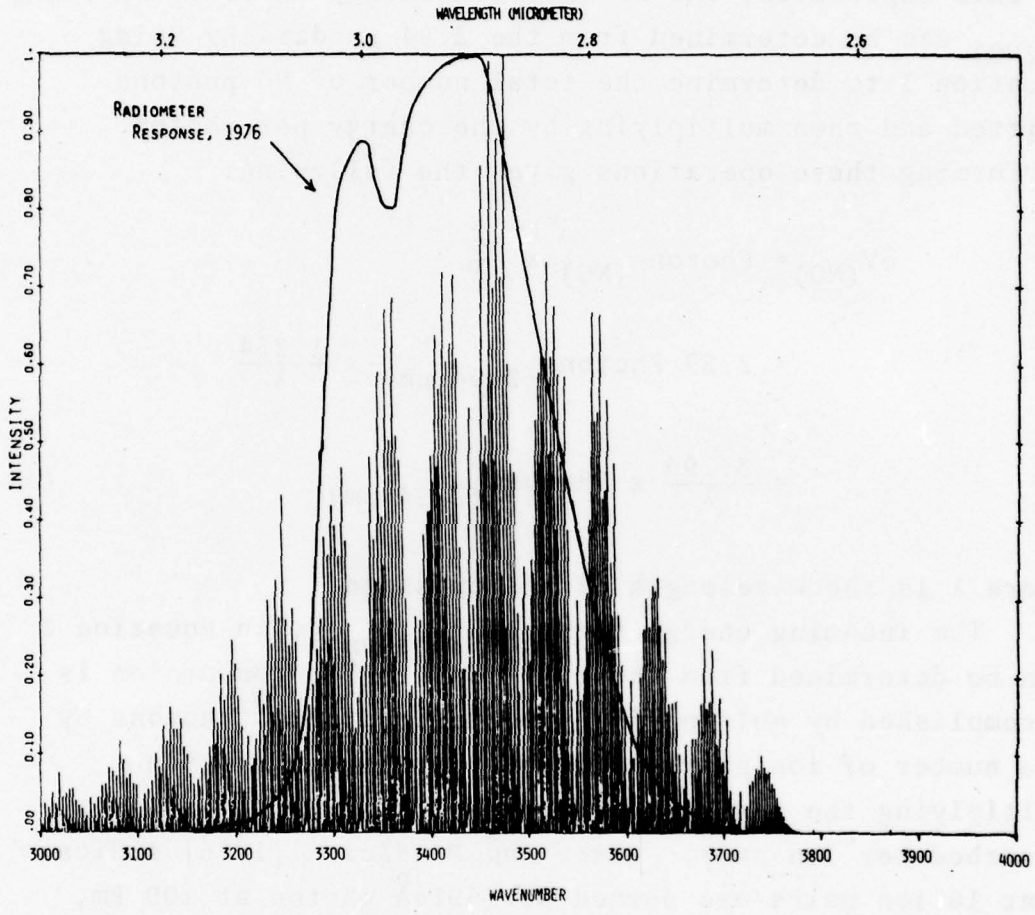

Figure 17. Radiometer response curves overlayed on a synthetic spectrum of NO $\Delta V = 2$ computed for $T_R = 220°K$, $T_V = 5000°K$, resolution = 1 cm^{-1}.

start with the following definition:

$$\text{Photo Energy Efficiency}_{(NO)} = \frac{eV_{(NO)}}{eV_{(incident)}} \times 100\% \quad (2)$$

In this expression, the NO emission energy in electron volts $eV_{(NO)}$ can be determined from the 2.94 μm data by using Equation 1 to determine the total number of NO photons emitted and then multiplying by the energy per photon. Performing these operations gives the following:

$$eV_{(NO)} = \text{Photons}_{(NO)} \times \frac{hc}{\lambda}$$

$$= 2.59 \text{ Photons}_{(2.94\ \mu m)} \times \frac{1.234}{\lambda}$$

$$= \frac{3.196}{\lambda} \times \text{Photons}_{(2.94\ \mu m)} \quad (3)$$

where λ is the wavelength of the emission.

The incoming energy term, $eV_{(incident)}$, in Equation 2 can be determined from the 3914Å data. The conversion is accomplished by multiplying the measured 3914Å photons by the number of ion pairs generated per photon and then multiplying the result by the number of electron volts absorbed per ion pair. *Baker and Pendleton* [1976] indicate that 18 ion pairs are formed per 3914Å photon at 100 km, and *Tarr et al.* [1974] indicates that 34 eV are absorbed per ion pair produced. Using these values we obtain the following expression for the total incident auroral energy:

$$eV_{(incident)} = \text{Photons}_{(3914)} \times \frac{18 \text{ ion pairs}}{3914\text{Å Photon}} \times \frac{34 \text{ eV}}{\text{ion pairs}}$$

$$= 612 \times \text{Photons}_{(3914)} \quad (4)$$

Substituting Equations 3 and 4 into Equation 2 gives the following expression:

$$\text{Photo-Energy Efficiency}_{(NO)} = \frac{.522}{\lambda} \times \frac{\text{Photons}_{(2.94\ \mu m)}}{\text{Photons}_{(3914)}} \quad (5)$$

This expression can be equally stated as follows:

$$\text{Photo-Energy Efficiency}_{(NO)} = \frac{.522}{\lambda} \times \frac{R_{(2.94\ \mu m)}}{R_{(3194\text{Å})}^{o}} \quad (6)$$

where $R_{(2.94\ \mu m)}$ is the measured 2.94 μm enhancement radiance in Rayleighs and $R_{(3914\text{Å})}^{o}$ is the measured radiance of the 3914Å (N_2^+) (0, 0) first negative band in Rayleighs.

Using Equation 6 and the ratios of the radiances given in Table 2, the percentage of incoming auroral energy that is radiated as NO first overtone photons was calculated for the seven time periods being analyzed. An average wavelength of 2.9 μm was used for λ in the calculations. The results are given in Table 3. As shown, the efficiencies vary from measurement period to measurement period. The largest value is 2.5 times the smallest value causing a 150 percent variation in the values.

Table 3. Photo-Energy Efficiency of Measured NO Enhancements

Date - Mission	Time (UT)	Efficiency (%)
3 Mar 76 - IC 76-6	0500 - 0530	.4
7 Mar 76 - IC 76-9	1000 - 1030	.55
	1120 - 1150	.55
8 Mar 76 - IC 76-10	0730 - 0800	.6
26 Mar 76 - IC 76-16	0905 - 0935	.8
	1010 - 1040	1.0
	1120 - 1150	.8

The question now arises as to what causes the large variation. Two potential causes worth considering are instrumentation response variations, and altitude dependencies of the reaction relative to varying auroral penetration depths.

Calibrations on all the instruments including the 3914Å photometer, the 1.7 μm radiometer, and the 2.94 μm radiometer were performed before and after the measurement series. The response and noise of each was found to remain constant. Thus, instrument response changes did not cause the large variations, but one related problem worth considering involves changes in the throughput of the LN_2 cooled chopper-baffle system which was operated in front of the 2.94 μm radiometer but not in front of the 1.7 μm and 3914Å instruments, as described by *Huppi and Reed* [1977]. Varying amounts of frost accumulation on the windows in the chopper assembly would effectively change the overall response of the 2.94 μm channel. However, the cold chopper windows were visably inspected during operation and generally found to remain clear. This is a good indication that the cold chopper did not cause the measured variations in the ratios of the 2.94 μm and 3914Å data and the corresponding calculated NO photo-energy efficiencies. This is further verified by the measured OH ratios given in Table 1. The maximum variation in the OH ratios for the seven measurement periods is 33 percent. This is considerably less than the 150 percent variation seen in the ratio of the background-subtracted 2.94 μm data and the 3914Å (N_2^+) data. If the chopper system caused the large variations in the photo energy efficiencies determined from the measured 2.94 μm/3914Å ratio, then similar variations would occur in the measured OH ratios. Both ratios are determined using the 2.94 μm radiometer data operated behind the cold chopper and data from an external photometer or radiometer. Thus, since the

large variations aren't seen in the OH ratios, the variations in NO photo-energy efficiency must be caused by actual changes in the atmospheric chemistry.

Variations in auroral penetration depth and altitude dependencies of the NO chemistry presently appear to be the most plausible cause of the observed variations of photo-energy efficiency. Some measurements for studying the altitude dependencies relative to the measured data have been made as discussed by *Huppi and Reed* [1977], but the analysis of the data has not been completed. Further coordinated measurements and analysis using infrared measurements from the aircraft and altitude electron density measurements from the Chatanika radar would be a good approach for defining the altitude dependencies. Another approach is to monitor at least three other aurorally enhanced emitters simultaneously with the 2.94 μm channel. The other emitters should be selected such that their radiation is generated from reactions occurring at various altitudes, thus providing information on penetration depths of the aurora. Photometric measurements including this type of data have been performed by Photometrics, Inc. for some of the measurement periods given in this report and should provide useful information for future coordinated analysis.

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