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The 1967 LASL-Sandia Rocket-Borne
Study of Vacuum Ultraviolet and
Visible Emissions in Auroras

UNITED STATES
ATOMIC ENERGY COMMISSION
CONTRACT W-7405-ENG. 36

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Printed in the United States of America. Available from
Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards, U. S. Department of Commerce
Springfield, Virginia 22151

Price: Printed Copy \$3.00; Microfiche \$0.65

Written: February 10, 1969
Distributed: April 18, 1969

LA-3929
UC-34, PHYSICS
TID-4500

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by

Karl Theobald

H. Milton Peek

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THE 1967 LASL-SANDIA ROCKET-BORNE STUDY OF VACUUM ULTRAVIOLET AND
VISIBLE EMISSIONS IN AURORAS

Karl Theobald and H. Milton Peek

ABSTRACT

Visible and vacuum ultraviolet emissions in an International Brightness Coefficient II aurora were measured in a joint Los Alamos Scientific Laboratory-Sandia Corporation rocket-borne experiment. The rocket payload was carried in a 12-in. Nike-Tomahawk to 167-km apogee at the Churchill Research Range, Fort Churchill, Manitoba, at 2147 CST on February 27, 1967. Instrumentation consisted of a scanning spectrometer for the 1150- to 1650-Å wavelength range; a filter-wheel photometer for 3914-Å first negative N_2^+ , 4059-Å second positive N_2 , and 5577- and 6300-Å atomic oxygen; and an electron spectrometer that failed.

Good altitude profiles were obtained for all wavelengths until the filter-wheel photometer failed at 140 km. This is the first good profile achieved for the Lyman-Birge-Hopfield N_2 system in an aurora. The total maximum photon flux density in this system was derived from five observed bands. From the 3914- and 4059-Å data, the total maximum flux densities were derived for the first negative N_2^+ and second positive N_2 systems. These values and those of other significant spectral emissions were:

N_2 Lyman-Birge-Hopfield system	8 kR
N_2 second positive system	6 kR
N_2^+ first negative system	6 kR
H Lyman alpha, 1216 Å	3 kR
Atomic Oxygen, 1304 Å	9 kR
5577 Å	11 kR
6300 Å	0.7 kR

The total measured photon flux in the vacuum ultraviolet was roughly equal to that in all visible bands and lines, indicating substantially greater energy radiated in the ultraviolet. Emissions at 3914, 4059, and 5577 Å have the same altitude dependence. When corrected for absorption by O_2 , the Lyman-Birge-Hopfield emission has the same altitude dependence as N_2^+ first negative. Comparison of measurements with calculations leads to the conclusion that cascading through the Janin and Gaydon-Herman bands into the upper state of the Lyman-Birge-Hopfield bands was not significant in this aurora. Emission from atomic oxygen at 5577 and 6300 Å does not come mainly from direct electron impact excitation, but the principal mechanisms are unknown.

INTRODUCTION

The Los Alamos Scientific Laboratory (LASL)-Sandia Corporation rocket program studies the aurora as an air fluorescence problem, with particular emphasis on the vacuum ultraviolet radiation first observed in auroras by Crosswhite et al.¹ Isler and Fastie² identified the principal emissions in the vacuum ultraviolet as the Lyman-Birge-Hopfield (LBH) bands of N_2 , with other contributions from OI and NI as well as the nonauroral 1216-Å hydrogen, Lyman α line.

In 1965 Peek and Hoerlin³ conducted two launchings with vacuum ultraviolet spectrometers for the LBH region and filter photometers for the 3914-Å band of the N_2^+ first negative system. (The first launching was coordinated with an Aerobee launch by Fastie carrying similar instrumentation; results of the Aerobee measurements have been reported by Miller, Fastie, and Isler.⁴) Both LASL flights gave good altitude profiles for 1304-Å OI, 1200-Å NI, and 1216-Å Lyman alpha, but poor signal-to-noise ratio in the detector electronics prevented determination of profiles for the LBH bands, and only an approximate upper limit for the peak photon flux density was established.

For the 1967 work reported here, coverage was extended to other wavelengths in the visible region, an electron spectrometer was added, and the performance of the ultraviolet spectrometer (UVS) was greatly improved by changing from analog to pulse-counting techniques. We hoped to correlate energies of the various spectral emissions and the electron flux. Because the electron spectrometer failed, only the spectral features could be compared, but the data are not without interest. For the first time, a clear altitude profile has been obtained for the LBH system, and another measurement has been added to several earlier ones that show a close connection between intensities of 3914 and 5577 Å, as discussed by Romick and Belon.⁵

INSTRUMENTATION

For the visible spectrum the rocket carried a five-position, filter-wheel photometer fitted with a Geneva drive. Four positions were used for interference filters of 35-Å full width at half maximum,

and the fifth was blocked for monitoring of dark current and scattered light. The wavelengths chosen were 3914 Å, the strongest band of the spectrum of N_2^+ ; 4059 Å, a fairly strong and well-isolated band of the N_2 second positive system; and the well-known auroral oxygen lines at 5577 and 6300 Å. The sensor was an EMR type-541 E photomultiplier whose output was read by a logarithmic electrometer and telemetered as an analog signal. The time required to scan all five positions was 1.3 sec.

A prime objective was to measure the energy in the LBH system of N_2 . Therefore, a 500-Å-wide band, centered at about 1400 Å, was scanned in 5.3 sec by a Fastie-Ebert spectrometer of 0.25-m focal length. This procedure did not cover the longer wavelength LBH bands, but their energies can be inferred from those in the region measured. In this region are also 1304-Å OI, 1216-Å hydrogen Lyman α , and other weaker lines of OI and NI. Pulses from an EMR type-542 G photomultiplier were counted for each 60-msec interval, and the resulting samples were telemetered as binary numbers. The theoretical resolution as a result of sample time and the 1-mm slit width was 12 Å. Actual resolution was somewhat poorer, probably because of imperfect alignment. The 1200-Å line of NI could not be resolved in the wing of the stronger 1216-Å Lyman α line. Dark count rate was less than one count per sec, compared with signal counts on the order of 200 to 20,000 per sec. Since the payload velocity at auroral altitudes was more than 1 km/sec, each spectrometer scan covered several kilometers in height and successive visible measurements were separated by about 1 km. Very active auroras have structure as fine as 100 m and fluctuate in as little as a few seconds. The instrumentation was intended to be applied to fairly stable conditions. The spectrometer and photometer employed fields of view of about 0.1 rad diam, which has a strong averaging influence on the data, particularly for the 1304- and 6300-Å emissions, which come from a high altitude.

Outgassing of payload components produces absorption around the instruments which is marked in the vacuum ultraviolet. Water vapor is probably the worst offender. To reduce this difficulty, the nose cone assembly was sealed and evacuated by means of an umbilical sublimation pump which was removed

40 sec before launch. This procedure eliminated outgassing in the instruments, which is probably the major source of absorption.

The nose cone was ejected at 86 km, and the high voltage was applied to the UVS photomultiplier 11 sec later, at 99 km. This procedure prevents arcing at the window seal, which could fog the window and invalidate the calibration.

Ground support included photometry, all-sky photography, and magnetometer recording, all supplied by the Churchill Research Range.

CALIBRATIONS

The filter-wheel photometer was calibrated in a straightforward manner using a standard lamp at 6 m and several calibrated neutral-density filters. The interference filters were calibrated and checked for bandpass and rejection of unwanted light with a Cary spectrophotometer. Light intensities covered the entire operating range from a few tens of Rayleighs (R) to about 100 kR. (1 R equals 10^8 photons/cm²/sec radiated into 4π sr. An International Brightness Coefficient II aurora (IBC II) is, by definition, 10 kR of 5577-Å emission.) Reproducibility and logarithmic response were excellent. Some nonlinearity was found at photo currents greater than 1 μ A, probably from optical feedback in the multiplier. This current level corresponds to IBC III, which is unlikely to be encountered in an auroral form suitable for rocket investigation.

The correction required to translate point-source to extended-source calibration is trivial for this instrument. The field of view was 2.5×10^{-3} sr, so penumbral effects were minor. Telemetry accuracy was about 0.1 V at 1 V/decade, or about ten times the calibration error.

The UVS was calibrated using a capillary discharge lamp with a LiF window and low pressure H₂ filling. The lamp was calibrated against a photomultiplier of known sensitivity using a Seya-McPherson monochromator of known transmission. At practical distances from the UVS the lamp was too bright, so a pinhole aperture was used in place of the entrance slit. This procedure does not illuminate the entire grating, mirror, or exit slit, but the pinhole can be moved so that several different areas can be

used. The pinhole aperture was removed before payload assembly, and for preflight checks a filter screen was used to reduce the intensity enough that the weaker lines of the spectrum could be used for sensitivity checks. The error involved is estimated to be a factor of two. At wavelengths shorter than 1216 Å the transmission of the optics is poor and rapidly falls to zero, so calibration is progressively poorer in this region. No significant deterioration in transmission with time was found in the preflight checks.

FLIGHT DATA

The instrument package was launched on a 12-in. Nike-Tomahawk at 2147 CST, February 27, 1967, reaching apogee at 167 km. It penetrated an aurora formed by the coalescence of two arcs of brightness II and descended through a less intense aurora. Magnetic activity began about 10 min before launch, with excursions of slightly over 100 γ in all three components. The ultraviolet spectrometer performed well throughout the flight. The filter-wheel photometer showed a shift in gain at 140 km on ascent, and its mode of recovery cannot be ascertained. The electron spectrometer failed, showing a complete loss of sensitivity.

The ultraviolet spectrum in the region of maximum intensity is shown in Fig. 1. Since the effective resolution of the UVS is about the same as the average separation of the Lyman-Birge-Hopfield bands, there is a good deal of overlapping, but the bands at 1384, 1463, 1531, and 1554 Å are well isolated and free from interference. Holland's⁶ laboratory measurements of the 900-eV electron excitation cross sections for these bands are consistent with the measured relative amplitudes and allow the total intensity in the LBH system to be calculated with good consistency, as shown in Table I.

Figure 2 shows the altitude profiles of the stronger features of the ultraviolet spectrum. 1216-Å (Lyman α) intensity is constant above altitudes where absorption is present. Its symmetry in ascent and descent shows that contaminants from the payload did not produce absorption. Its intensity is about twice that reported by Peek and Hoerlin,³ but falls in the range of values summarized by Donahue.⁷ 1304-Å OI shows the smoothing effect of

Fig. 1. Vacuum ultraviolet spectrum with altitude range covered during scan.

resonance scattering, with some absorption below 120 km. The LBH bands at 1384 and 1355 Å should be of nearly equal intensity according to Holland's cross sections,⁸ and the difference is attributed to the OI line near 1355 Å. Other features of NI and OI have profiles similar to those of 1384 and 1355 Å

Table I. Measured and Total LBH Emission

LBH Band	Wavelength (Å)	Measured Flux (kR)	Calculated Total IBH System Flux (kR)
(4,0)	1325	0.41 ^a	9 ^a
(5,2) + (2,0)	1384	0.39	7
(1,1)	1464	0.32	8
(2,3) + (6,6)	1531	0.22	8
(4,5) + (0,2)	1554	0.20	8

^aCorrected for overlap with 1321-Å NI.

Fig. 2. Altitude profiles of the strongest features of the vacuum ultraviolet spectrum.

but rather low intensities, producing statistical intensity fluctuations. Profiles of these features and the descent portion of the 1384 Å data are omitted because of poor statistics.

Figure 3 shows altitude profiles reduced from the filter-wheel photometer data. All four curves show an intensity increase by a factor of four at 140 km. The ultraviolet spectrometer showed no such occurrence, and the 6300-Å OI line, coming from a state with a lifetime of over 100 sec, can hardly follow such a sudden increase in excitation. We must therefore conclude that the amplifier gain changed at this point, which necessitates an evaluation of instrument performance before the change.

Two arguments can be made to support the contention that the filter-wheel photometer was performing as expected at altitudes below 140 km on ascent. One involves a comparison of the filter-wheel photometer data with similar data from the ground-based Churchill Research Range photometer, and the other involves comparison between filter-

Fig. 3. Altitude profiles for N_2 bands and OI lines. wheel photometer altitude profiles for 3914 Å and UVS profiles for isolated IBH bands.

The 3914-Å ground-based photometer had a field of view of 0.1 rad and was pointed along a line of sight which intersected the predicted rocket trajectory at 100 km altitude. The actual position of the payload at that altitude was within 2 km horizontally of the predicted position. Both the cone angle of the payload and the angle between the photometer lines of sight were a few degrees. As a result, during most of the ascent, the fields of view of rocket-borne and surface photometers included the same area of the sky. The aurora showed fibrous structure too fine to be resolved by the photometers and was of uniform average brightness over a wide area around the rocket trajectory. We conclude that meaningful comparison between flight and ground instruments is possible.

Ground photometer data agreed well with those of the flight photometer until the payload reached 110 km. Then the flight instrument readings decreased in intensity while the ground photometer reading continued to increase for 10 sec, after which it fell and rose again over a small range. A sharp drop at apogee time was recorded by all instruments, even though the payload field of view did

not include the surface photometer field of view at that time. Up to 110 km, then, the payload photometer seemed to be functioning well. The base of the aurora was apparently at that altitude.

Possibly a drift in the flight instrument began at 110 km, and the shift at 140 km represented a recovery. This is unlikely because 110 km is a reasonable lower limit for an aurora, and the argument shows that the 3914-Å altitude profile recorded by the flight instrument is consistent with the 1304-Å IBH profile recorded by the ultraviolet spectrometer until the photometer shift occurred.

The 3914-Å altitude profile below 140 km is similar to that of the columnar density of molecular nitrogen, suggesting an auroral model in which the probability of excitation is not a function of altitude. For such a model the ground-based photometer signal is proportional to the column integrated excitation, and the flight photometer detector signal is proportional to the product of the excitation and the columnar density of N_2 above the rocket. Figure 4 shows the ground-based photometer signal plotted against payload altitude above 110 km, the flight

Fig. 4. Comparison of surface and flight photometer intensities at 3914 Å with calculated altitude profile.

photometer record, and the 3914-Å profile calculated from the model and scaled to the flight record. Nicolet's model atmosphere, as quoted by Chamberlain,⁸ was used arbitrarily. No better agreement could be expected, and the model will be regarded as the best fit for the photometer data.

If the flight photometer functioned properly, the same auroral model must give the proper altitude profile for the IBH bands. Since most excitation is produced by secondary electrons, a change in primary energy will have only a small effect on the 3914 Å/IBH ratio, so a constant probability of excitation to the $A^1\Pi_g$ upper state of the IBH system is a reasonable concomitant to the model. This state has a lifetime of about 0.2 msec, which is short compared to the time between collisions at auroral altitudes, so collisional quenching is probably negligible. Schumann-Runge absorption by molecular oxygen is not negligible, as shown by the sharp decrease in IBH intensity below 112 km in Fig. 2. Thus, using the same model for excitation as before, the IBH signal will be proportional to the product of the excitation, the ratio of excitation probabilities of IBH and 3914 Å, and the absorption of IBH photons by O₂. With this model, Nicolet's atmosphere, and Schumann-Runge absorption coefficients from Goldstein and Mastrup,⁹ the IBH altitude profile shown in Fig. 5 is calculated. It is scaled to agree with the observed 1384-Å data, shown with statistical error bars, at 140 km. Agreement is satisfactory, and we conclude that the filter-wheel photometer data below 140 km are consistent with those of the ultraviolet spectrometer since both are consistent with the same model.

Since (1) the flight photometer profile correlates well with the ground photometer data, (2) the flight photometer and the ground photometer data have the same magnitude when the rocket is below 110 km, and (3) the flight photometer data correlate well with the IBH data from the UVS, we conclude that the flight photometer data before the shift at 140 km are to be accepted, and data after the shift are to be discarded.

DISCUSSION

One interesting, but difficult, problem in analysis of auroral radiation data is the radiation

Fig. 5. Calculated 1384-Å IBH (2,0) compared to measured data. Error bars denote statistical error.

energy balance; that is, what fraction of the incident electron energy is radiated in the various atomic and molecular lines and band systems of air? This problem has been treated theoretically by Chamberlain,⁸ and Green and Barth,¹⁰ and Stolarski and Green,¹¹ to name a few. Their results indicate that the radiations measured in these experiments are only 10 to 20% of the total radiation in an aurora. Consequently, it does not seem possible to make a complete model of the radiation energy balance from these data alone. An additional complication is the effect of resonance scattering which must be considered in calculating the volume emission rates from the measured photon flux densities. Preliminary work by Thomas¹² in analysis of the 1965 auroral data³ indicates that the resonance scattering effect is very large for the 1304-Å atomic oxygen line and the 1200-Å atomic nitrogen line, but the magnitude must be determined from a detailed analysis which we have not attempted for these data. Accordingly, we point out some useful comparisons of data with theory where resonance scattering is not significant.

From the measured energy of 3.8 kR in the 3914-Å first negative band, the total first negative energy is estimated to be 6 kR. Hartmann's data¹³ on N₂ second positive system fluorescence show that the 4059-Å emission is 2 or 3% of the total system emission. Therefore, the measured 150 R implies about 6 kR total in this system. As shown earlier, our measured emission of IBH indicates a total system emission of about 8 kR, with an uncertainty of a factor of two. Within the uncertainty of the measurements, all three systems have the same emission. The results of Miller, Fastie, and Isler⁴ also show approximately the same energy in the IBH and first negative systems.

The populations of the ground states for the first negative and second positive systems are very small and the IBH bands arise from forbidden transitions; therefore, the optical thicknesses for these emissions are small; i.e., the atmosphere is thin. In this case the relative volume emission rates are proportional to the relative photon flux densities, and we can compare our results with the calculations of expected emission strengths reported by Green et al.^{10,11} Experimental confirmation of the expected thickness is provided by the fact that the altitude profiles of 3914-, 4059-, and 1384-Å emissions (1384 Å corrected for O₂ absorption, see Fig. 5) have the same shape. These emissions are believed to be excited by electron impact on N₂, which implies that the volume emission is proportional to the excitation cross section and to the altitude profile of molecular nitrogen density. Thus, in the absence of resonance scattering, the altitude profiles of photon flux density should have the same shape.

Green and Barth¹⁰ calculate about five times as much IBH as first negative, ignoring the possible effects of cascading from the higher excited singlet states of N₂. Including estimated effects of cascading leads to a factor of about 30 times as much IBH as first negative. Somewhat refined calculations reported by Stolarski and Green¹¹ and Green, Peterson, and Prasad¹⁴ give a factor of about 10 including cascading and of about 1.5 neglecting cascading. Since our data show about the same IBH as first negative, we conclude that cascading from the b¹Π_g and h¹Σ_u states of N₂ (through the Janin

and Gaydon-Herman bands) into the a¹Π_g state of the IBH system was not an important process in these auroras.

Calculations by Green et al.^{10,11,14} as well as most ground-based auroral measurements lead to the conclusion that the 5577-Å emission from atomic oxygen has about the same strength as the total first negative system. Although our data show the same agreement, it is important to note that this agreement is independent of altitude. If 5577-Å emission were electron excited, the ratio of 3914 to 5577 Å should depend on altitude because the atomic oxygen concentration falls off with altitude much more rapidly than does the concentration of N₂. Consequently, we conclude that 5577-Å emission is not primarily due to electron excitation of ground-state atomic oxygen. This same conclusion has been reached by Donahue et al.,¹⁵ who propose that the 5577-Å radiation arises from dissociative recombination of O₂⁺. More recent work by Brekke and Omholt¹⁶ and by Stolarski¹⁷ leads to the conclusion that while dissociative recombination is probably significant in auroral 5577-Å emission, it is not the controlling process. Brekke and Omholt¹⁶ conclude that the principal mechanism is still unknown.

It does not seem possible to make pertinent contributions to elucidation of the 6300-Å mechanism on the basis of our data alone because they are restricted to altitudes below 140 km where quenching of the 6300-Å radiation is so strong that only a few percent of the excited ¹D oxygen atoms can radiate. The variation shown in the 6300-Å data plotted in Fig. 3 is believed due to horizontal rocket motion or to a temporal variation in intensity, rather than a true altitude variation.

From a phenomenological point of view, it is interesting to summarize the observed maximum photon flux densities and to compare photon flux densities and inferred total band system results for several different auroras. Table II lists the data from the 1967 rocket flights, and Table III compares data from 1965, 1967, and 1968 flights. The 1968 vacuum ultraviolet data are based on preliminary field analysis and may change somewhat upon completion of more careful reduction.

Table II. Observed Intensities at Maximum Auroral Brightness

CONCLUSION

Wavelength (Å)	Intensity (kR)	Accuracy
Atomic Lines in the Vacuum Ultraviolet		
1200 NI	1.5 (max)	2x
1216 HI	3	
1240 NI	0.2	
1495 NI	0.5	
1304 OI	9	
1355 OI	1 (IBH 3,0 subtracted)	
Lyman-Birge-Hopfield N ₂ Bands		
1384 (2,0)	0.4	2x
1463 (1,1)	0.3	
1531 (2,3)	0.2	
1555 (0,2)	0.2	
Total IBH	8	
N ₂ Bands in the Visible		
First Negative System of N ₂	6	10%
Second Positive System of N ₂	6	20%
Atomic Lines in the Visible		
5577 OI	11	10%
6300 OI	0.7	

It is clear that no single rocket package can measure all of the important auroral parameters. Thorough data analysis for the emissions at 6300 and 1304 Å requires that the rocket reach altitudes of about 400 km, while only about 160 km is necessary for data on 5577 and 3914 Å. Payload weight and telemetry requirements definitely limit the number of instruments that can be carried. Soon it will be possible to fire two rockets of the same type simultaneously from the Churchill range, opening up new channels for coordination of experiments.

Further improvements are being made in vacuum ultraviolet instrument capability, including unsupported metal filters and spectrometers for wavelengths less than 1100 Å. We also hope to measure the altitude dependence of the N₂ first positive and Vegard-Kaplan systems.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the work of Herman Hoerlin, the LASL project director, in planning of the experiment, in arranging financial support, and in helpful discussions on the preparation

Table III. Intensities Observed at 130 km in Five Flights

Wavelength	1965				1967	1968			
	A Ascent (kR)	A Descent (kR)	B Ascent (kR)	D Descent (kR)	Ascent (kR)	A Ascent (kR)	A Descent (kR)	B Ascent (kR)	B Descent (kR)
1200 NI	0.7	0.7	0.7	0.3	NR ^a	0.3	0.4	NR	NR
1216 HI	1	1	0.7 ^b	1.1	3	3	3	13	13
1304 OI	8	8	5	0.9	9	4	6	4	3
LBH	NR	NR	NR	NR	2.7	1.5	4	2	2
3914N ₂ ⁺	4	1.5	4	1.5	0.5	0.5	1.4	0.67	0.4
First Negative	6.7	2.5	6.7	2.5	0.8	0.8	2.3	1.1	0.7
4059 N ₂		not measured ^a				0.02	0.03	0.08	0.09
Second Positive		"	"		0.8	1.2 ^c	3.2	3.6	3.2
5577 OI		"	"		1.5	1.4	5	2.3	1.4
6300 OI		"	"		0.3	0.9	1.5	10	5

^a NR means no measurable signal; not measured means that no instrument with that capability was included in the payload.

^b This record shows signs of absorption on ascent.

^c The comparatively high second positive intensities in the 1968 data are quite possibly due to inadequate correction for dark current. (4059/3914 intensity ratios for these flights show intensity dependence.) Data analysis is not complete.

of this report. The expert services of the Sandia Corporation team, directed by V. K. Smith and T. C. Looney, were invaluable. We are grateful for the essential contributions by Dr. J. H. Brandy, Churchill Research Range Superintendent; James Hillis of Pan American World Airways; their very helpful staffs; and H. L. Fishbine of LASL for assistance in preparations and field work.

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