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N71-19748

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TECHNICAL REPORT No. 25

NASA Research Grant NGR 21-001-001

Some Spectrometric Results from the NASA 1968 Airborne Auroral Expedition and Tentative Identification of Several N_2 $c'\,^1\Sigma_u^+ \rightarrow a\,^1\Pi_g$ Bands in Auroras

by

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August 1970

Baltimore, Maryland 21218

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and

TENTATIVE IDENTIFICATION OF SEVERAL $N_2\ c'\ {}^1\Sigma_u^+ \rightarrow a\ {}^1\Pi_g$ BANDS IN AURORAS

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To be published in the Journal of Geophysical Research

FOREWORD

This technical report is a preprint of two manuscripts which have been accepted by the Journal of Geophysical Research for publication. The first paper represents results from airborne measurements in the NASA 990 aircraft and the second paper combines measurements taken in the aircraft with rocket measurements to identify previously unidentified auroral features.

Wm. G. Fastie
Principal Investigator

Some Spectrometric Results from the

NASA 1968 Airborne Auroral Expedition

ABSTRACT

Spectrophotometer measurements taken aboard NASA's 1968 Airborne Auroral Expedition included numerous weak auroral features. The permitted OI line at 4368 Å was found to have an intensity ratio to the N_2^+ 1NG (0,1) band at 4278 Å of 1:60 under a variety of auroral conditions. The forbidden NI line at 3466 Å was seen to vary in intensity relative to 4278. Its variation follows OI 6300 Å, and may be used as an indicator of precipitating electron energy changes. The continuum at 6700 Å was found to have a value $<$ 1/2 R/Å in an area through which an arc had recently passed. A technical report will shortly be available giving more details of results at the disposal of other experimenters.

INTRODUCTION

During the period January–March 1968, an Airborne Auroral Expedition was flown aboard NASA's Convair 990 aircraft 'Galileo.' The instruments used by the Johns Hopkins University group consisted of a one-meter scanning Ebert spectrophotometer and a five-position filter-wheel photometer. These instruments have previously been described in more detail [*Dick et al.*, 1970]. The photometer monitored the features OI 5577, 6300 Å; N_2 1PG (5,2) 6704 Å; N_2 2PG (0,0) 3371 Å; and N_2^+ 1NG (0,0) 3914 Å, remaining on each position for two seconds. The spectrometer scanned the first order region 12,400–14,000 Å every fifteen seconds with the capability of selectively admitting only second, third, or fourth order wavelength intervals through color glass filters. Most of the results reported herein, however, were taken from times when no such filters were in use.

Of the 124 hours flown during this expedition, some 30 represented daylight, ferry, practice, or aborted flights, and take-off and landing times. In addition, approximately 28 hours were flown under conditions where only night-sky observations were possible. The results under these conditions have been presented elsewhere [*Dick et al.*, 1970]. The remaining time was flown under auroral conditions varying from minimum detectable forms to patches with intensity near

IBC III. It is not planned at this time to digitize all the remaining data (currently stored on analogue magnetic tape), but rather to look at selected periods for specific purposes. The periods rejected for initial study include both those where the intensity is so low as to make accuracy of measurement difficult even on summed averages, and those where fluctuations in intensity were significant over a spectral scan time.

In addition to presenting the results below, one of the purposes of this brief report is to make known the availability of Technical Report No. 24, NASA Research Grant NGR 21-001-001, of the Johns Hopkins University, Department of Physics. This report summarizes the data for the entire expedition, and is available to anyone wishing to consider the data alone or in conjunction with those of other expedition experimenters.

RESULTS

The results for OI 4368 Å and NI 3466 Å are from fifteen periods of auroral activity chosen from the total time reduced. Each period represents summation over a period from 30 seconds to 15 minutes where the features discussed were measured simultaneously.

OI 4368 Å

The permitted atomic oxygen transition (3s $^3S^0$ - 4p ^3P) at 4368 Å was contained in the spectral region scanned. Its measurement was complicated by other spectral features in several overlapping orders, but a number of time-averaged values were obtained. The resolution was between one and three Å, depending on slit width. Our results show a ratio 4278/4368 of 60 with a standard deviation of 14.

Although little theoretical work has been done in general on permitted oxygen lines, *Stolarski and Green* [1967] predicted the intensity of the (3s $^3S^0$ - 3p ^3P) line at 8447 Å for various incident electron energies and calculated it to be several times as intense as N_2^+ 1NG (0,1) 4278 Å for the atmospheric composition chosen (45% N_2, 45% O, 10% O_2). Assuming both the 3p ^3P and 4p ^3P to be excited by secondary electrons colliding with ground state OI (^3P), and knowing the energies involved

(11.0 ev for 3p ^3P and 12.4 ev for 4p ^3P), the direct excitation rates for the two levels might be expected to be comparable. However, excitation into the ns $^3S^0$ and nd $^3D^0$ levels, followed by cascade emissions, may be the dominant means of populating the np ^3P levels. Further, the 4p level has a competing transition at 2.9μ to the 4s $^3S^0$ level, which may subsequently radiate at 1.3μ to further populate 3p ^3P. The relative transition probabilities of the 4368 Å and 2.9μ lines are not known, but approximate values may be calculated using the method of *Bates and Damgaard* [1949]. These calculations give A(2.9μ)/A(4368) ∿ 5. (A further transition at 4.6μ to 3d $^3D^0$ is small compared to both 2.9μ and 4368.) This would set a lower limit of I(8447)/(4368) = 5 if comparable population rates are assumed. This is comparable with a ratio of 6 determined photographically by *Petrie and Small* [1953].

Data from a rocket flight (4.162) indicate an upper limit for I(8447)/I(4278) of 0.1 (T. D. Parkinson, private communication). Combined with the above values, this would predict I(4278)/I(4368) $\gtrsim$ 50. These results therefore all appear compatible, and indicate that OI 8447 is at least an order of magnitude less intense than 4278. (It should be noted, however, that *Vegard* [1961] reported a ratio of 4278 to 4368 from photographic plates of only about 20, a factor of 3 lower than that reported here.)

NI 3466 Å

Eather [1969] reports the observation of enhanced auroral OI 6300 Å emissions inside the normal auroral oval, and notes that this agrees with satellite measurements of low energy auroral electrons. Our observations of 6300 showed the same characteristics. Since the forbidden atomic nitrogen line (^4S - ^2P) at 3466 Å was in our spectral scan range (in fourth order), we decided to see if the ratio 3466/4278 also increased in the same region. However, the weak 3466 feature could not accurately be measured on a sufficient number of occasions in the weak auroras in the 'soft auroral zone' to produce meaningful results. What was possible, however, was to consider the ratio 3466/4278 under all auroral conditions, and compare with 6300/4278. The results are shown in Figure 1. (It should be noted that this is really equivalent to plotting 3466 *vs.* 6300, but plotting the ratio with 4278 both allows presentation on a linear scale and retains the concept of its usefulness as an electron energy indicator.) In general, the high ratios were obtained from weaker auroral forms, and are less accurate than those with lower ratios. From the graph, a value of I(3466)/I(6300) ≃ 1/18 is obtained.

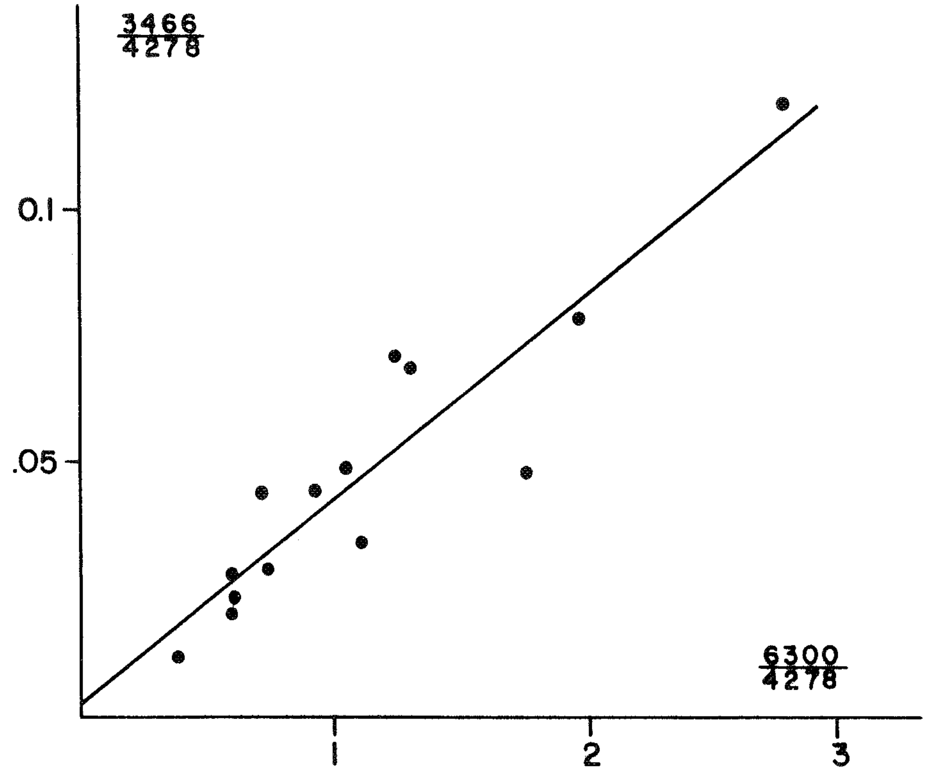

Fig. 1. Spectral intensity ratios of 3466 and 6300 with respect to 4278.

Although 3466 is a weaker feature than 6300 (and therefore more difficult to measure accurately),† it has the advantage of not being a feature of the night sky. It was often found difficult to assess the airglow 6300 contribution when there had been continuous auroral activity during the flight, although for the points used in Fig. 1 (representing 6300 intensities varying from 200 to 2200 R), the uncertainty introduced was less than 10%. Further, spectrometer studies

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† Note that the increased atmospheric attenuation at 3466 is approximately offset by increased photomultiplier quantum efficiency.

of spectral features in the ultraviolet have in 3466 an indicator of particle energies, and therefore need not be supplemented by measurements of 6300. Unfortunately, little is known quantitatively about quenching of NI (^2P) by atmospheric species [*cf. Hunten and McElroy*, 1966, and *Zipf*, 1969].

Continuum at 6700 Å

Donahue et al. [1970] suggest that the high measured NO^+ density in an auroral form may be the result of large NO densities at auroral latitudes. This could lead to the exothermic reaction

$$NO + O \rightarrow NO_2^*$$

with subsequent continuum radiation [*cf. Stewart*, 1957]. While the quantitative aspects of this process have not yet been fully determined (E. C. Zipf, private communication), it is useful to establish an upper limit to observed continuum emission in the auroral zone.

Since the spectrometer had no shutter to provide zero-light signal levels, direct continuum measurement was impossible. Also, when there was significant auroral activity, any continuum level would be overwhelmed by spectral features, notably N_2 1PG bands. Our procedure was to choose a point of low activity which had earlier seen a more active aurora, with the requirement that the second order filter was in the spectrometer. We then subtracted the N_2 1PG (5,2) band intensity as measured by the spectrometer from the total signal seen through the photometer band-pass. This was done for a point (~67°N, 57°W geomagnetic) crossed twice during flight 20, approximately an hour elapsing between passes. On the first pass, auroral activity was ∿1 kr (5577). On the second, near-airglow levels were reached. The measured N_2 1PG accounted for only one-third the total intensity seen through the interference filter, the remaining giving a level slightly less than 1 R/Å. The minimum signal seen through this filter under non-auroral conditions for the entire expedition, including low-latitude flights, was 2/3 R/Å. Hence a conservative estimate for an upper limit to a continuum contribution from NO_2^* would be 1/2 R/Å at 6700 Å. It remains to be seen whether this limit is low enough to make an estimate on the maximum NO density in the auroral regions. (Results from the 1969 Airborne Auroral Expedition, obtained directly with modified equipment, confirm this upper limit.)

N_2^+ 4278, 4236 Å

Because of the experimental results of *Moore and Doering* [1969] on the vibrational excitation of N_2 by collisions with low energy ions, the ratio of the N_2^+ 1NG bands (0,1) at 4278 Å and (1,2) at 4236 Å was determined for those times in the expedition when there was enhanced H_α emission. The values of the ratio N_2^+/H_β of *Eather* [1968] and of H_α/H_β of *Eather* [1969] were adopted in determining when there was a significant proton induced contribution to total auroral intensity. No evidence was found of the ratio 4236/4278 rising above the level of 0.14 quoted by *Moore and Doering* [1969] for protons with energies $\gtrsim$ 3 KeV.

FINAL REMARKS

The full implications of the intensity values, and variations in those values, of the features OI 4368 and NI 3466 herein reported are not assessable at this time. The necessary laboratory and/or theoretical data needed to relate them to other features in their respective systems, and to the incoming particle energetics, are not available. The results from this expedition, providing simultaneous coverage of nearly the entire accessible spectral range by the several experimental groups, may provide a source for data with which to compare future proposed auroral mechanisms.

The previously mentioned technical report lists all spectral features identified from the expedition records. Many, such as the N_2 VK (3,15) band at 4534 Å, are identifiable only on the most intense scans, where rapid fluctuations (less than the 15 sec. scan time) make quantitative investigation impossible. The intense features clearly evident are listed in Table I. The total number of identified features exceeds 40.

TABLE 1. Strongest Features in the Spectrometer Scan Ranges

λ (Å)	Identification
3136	N_2 2PG (2,1)
3159	N_2 2PG (1,0)
3371	N_2 2PG (0,0)
3466	NI $^4S^0$ - $^2P^0$
4236	N_2^+ 1NG (1,2)
4278	N_2^+ 1NG (0,1)
6300, 6364	OI ^3P - ^1D

Acknowledgments. The author benefited from working with W. G. Fastie on the expedition. The support of the personnel of the Airborne Science Office, NASA Ames Research Center, is gratefully acknowledged. Participation was made possible by NASA under Research Grant NGR 21-001-001.

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Tentative Identification of Several

N_2 c' $^1\Sigma_u^+ \rightarrow$ a $^1\Pi_g$ Bands in Auroras

ABSTRACT

Tentative identification of two bands of the N_2 c' $^1\Sigma_u^+ \rightarrow$ a $^1\Pi_g$ system has been made from auroral spectrometer results. The (0,0) band at 2827 Å was identified on a spectrum taken aboard an Aerobee sounding rocket (4.163) flown from Fort Churchill in February, 1967. The (0,2) band at 3119 Å was found on some averaged spectra taken during the NASA 1968 Airborne Auroral Expedition. Estimates of the intensities of these very weak bands show each to be $\sim$(.2 - .5)% as intense as the N_2 second positive system.

Observational Evidence

A half-meter Ebert spectrometer was flown aboard an Aerobee 150 sounding rocket into an active aurora at Fort Churchill on February 16, 1967. Although the photomultiplier signal became noisy during flight, a good scan of the region λλ 2200 - 3400 Å was obtained when the rocket was at ~90 km during ascent. Features clearly present included members of the Δv = 1 and 2 sequences of the N_2 second positive group and the (0,7), (0,6), (0,5) and (0,4) bands of the N_2 Vegard-Kaplan system. With spectral resolution of ~4 Å, the 2PG bands exhibited red peaks, degraded to the violet, while the VK bands appeared broad. The most obvious feature not associated with either of the above systems was a peak at 2827 Å. While this wavelength coincided with the (0,0) band of the system previously referred to as the 35371 cm^{-1} progression ($c\ ^1\Sigma \rightarrow a\ ^1\Pi$) of the Gaydon-Herman singlet systems, there seemed little justification in assigning this identification on the basis of the one band, especially since other bands of the Gaydon-Herman systems were not observed. Figure 1 shows a portion of the spectrum traced from a strip-chart record. Large noise spikes have been removed. Where it was not possible to judge the signal level below these noise spikes, gaps have been left in the tracing.

Fig. 1. Segment of the rocket spectrum from ~2740 - 2990 Å. Large noise spikes have been removed (see text). Peak intensity at 2972 Å in ~1.2 kR.

A recent investigation of the electron energy-loss spectrum of N_2 [*Williams and Doering*, 1969] shows a peak at 12.93 eV. A similar study under higher energy resolution [*Geiger and Schröder*, 1969] shows this peak to consist of components at 12.910 and 12.934 eV, with the latter accounting for ~75% of the energy-loss. In fact, the 12.935 eV component is several times as large as any other feature in the energy-loss spectrum in the region 12.50 - 14.86 eV. This level has recently been re-designated $c' \, {}^1\Sigma_u^+$ (v = 0) by *Dressler* [1969]. On the basis of these results, it becomes reasonable to expect that bands originating from this level would be stronger than those originating from other progressions of the Gaydon-Herman systems.

In order to make the observation of the (0,0) band convincing, however, it is also necessary to account for the lack of observation of the (0,1) and (0,2) bands in the spectrum. These bands have laboratory intensities of at least one-half that of the (0,0) band [*Pearse and Gaydon*, 1963]. The (0,1) band at 2967 Å lies close to the OI 2972 Å line and on the Δv = 2 sequence of N_2 2PG. Since the observed intensity of the (0,0) band is at least an order of magnitude less than the OI - 2PG (2,0) combination, the 2967 Å band would not be evident on this spectral scan. The (0,2) band at 3119 Å lies within 2 Å of the peak of the 2PG (3,2) band, and would not be resolved. Further members of the v' = 0 sequence lie further to the red, where the rapidly decreasing quantum efficiency of the Cs-Te photomultiplier tube would preclude observation.

Thus it becomes reasonable to expect that, of the various bands collectively attributed to the Gaydon-Herman systems, only the (0,0) band of the $c' \, {}^1\Sigma_u^+ \rightarrow a \, {}^1\Pi_g$ system would be observable on this spectral scan.

During NASA's 1968 Airborne Auroral Expedition, a one-meter Ebert spectrometer was flown which normally scanned the spectral region nλ = 12,400 to 14,000 Å [*cf. Dick et al.*, 1970]. Under active auroral conditions, this spectrometer was usually operated without its optional order-sorting glass color filters. The usual data-reduction procedure has been to sum a series of spectral scans over times of fairly constant auroral conditions during which instrument parameters such as slit width and signal gain were kept constant. During the longest such time (early in flight 22) a very clean spectrum was obtained under slit conditions corresponding to a fourth order resolution of slightly less than 2 Å at 3118 Å. This spectrum exhibits a clear shoulder to the red of the peak of the 2PG (3,2) band at 3116.7 Å, at a wavelength of ~3119 Å. Of course, this feature could arise from 4157 Å or 6238 Å, the overlapping third and second order wavelengths respectively. While the author is not aware of any reported auroral features at either of these wavelengths, it is acknowledged that the same argument used herein to assign the feature to a previously undetected emission at 3119 Å could equally be used to support some new line or band in either of the other orders. The detection of this feature alone could not be used to justify an identification of emissions from the Gaydon-Herman system, but in this instance provides corroborative evidence to the band assignment suggested by the rocket data. Figure 2 shows a portion of the summed spectra.

The only other bands of the sequence in the spectral range of the aircraft spectrometer are the (0,3) band at 3283 Å and the (0,4) band at 3463 Å. As well as probably being less intense than the (0,2) band, the (0,3) lies on emissions of the $\Delta v = 3$ sequence of N_2 1PG in second order, while the (0,4) lies on the N_2^+ Meinel (3,0) band. So here again the lack of identification of these other bands does not jeopardize the identification of the (0,2) band.

The intensity of the (0,0) band from the rocket spectrum is estimated to be between 1/4 and 1/2 that of the 2PG (3,1) band. The (0,2) band is estimated to be between 1/5 and 1/3 as intense as the 2PG (3,2) band. Since each of these 2PG bands contains ~1% of the intensity of the total 2PG [*Benesch et al.*, 1966] the bands reported here appear to be ~(.2 - .5)% as intense as the 2PG.

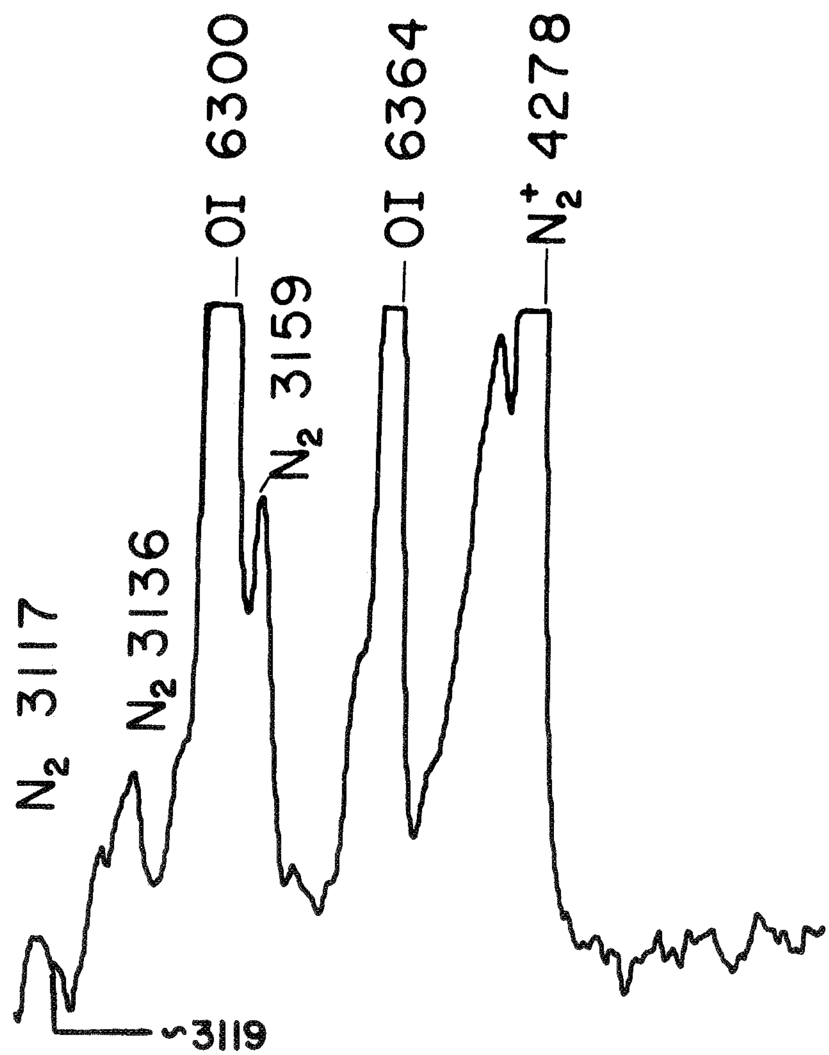

Fig. 2. Segment of the summation of 256 spectral scans early in flight 22. Integrated intensity of 4278 Å is ~1.3 kR. Structure to longer wavelength of 4278 Å is attributable to N_2 1PG emission.

Comments

While the evidence presented above cannot be considered conclusive in establishing transitions in the c′ $^1\Sigma_u^+ \rightarrow a\ ^1\Pi_g$ system as auroral features, the details are consistent, and sufficient to support tentative identification of the bands. The only previous report of emissions arising from these singlet states of N_2 is that of *Miller et al.* [1968] which tentatively identifies a band of the Birge-Hopfield system and one of the Watson-Koontz system. All these identifications of emissions arising from the singlet states indicate that their part played in balancing an auroral energy budget is small. However, in light of the above identification and the electron energy-loss spectrum, it would be interesting to know the intensity of the c′ $^1\Sigma_u^+ \rightarrow X\ ^1\Sigma_g^+$ (0,0) band at 958.2 Å.

Acknowledgements. The experimental work herein reported was done while the author was with the Johns Hopkins University under NASA Grant NGR 21-001-001, directed by William G. Fastie. The aircraft flights were managed by M. Bader and L. C. Haughney of the Airborne Science Office, NASA Ames Research Center.

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