N71-18995
NASA CR-116858

THE JOHNS HOPKINS UNIVERSITY

DEPARTMENT OF PHYSICS

TECHNICAL REPORT No. 28

NASA Research Grant NGR 21-001-001

ROCKET MEASUREMENT OF THE SECONDARY ELECTRON SPECTRUM IN AN AURORA

by

P. D. Feldman, J. P. Doering,
and J. H. Moore

October 1970

Baltimore, Maryland 21218

TECHNICAL REPORT

No. 26

ROCKET MEASUREMENT OF THE SECONDARY ELECTRON SPECTRUM IN AN AURORA

by

P. D. Feldman, J. P. Doering, and J. H. Moore*

The Johns Hopkins University
Department of Physics
Baltimore, Maryland 21218

October 1970

NASA Research Grant NGR 21-001-001

*Present address: University of Maryland
College Park, Maryland

To be published in the Journal of Geophysical Research

ABSTRACT

The differential flux of secondary electrons with energy greater than 6 eV was measured in a steady IBC I^+ aurora with an electron spectrometer aboard an Aerobee rocket. Except for the absence of structure in the energy range 10-20 eV, the observed spectrum is in excellent agreement with a recent theoretical prediction. About one-half of the observed N_2^+ emission at 3914 A can be accounted for by secondary electron excitation.

I. INTRODUCTION

Excitation by secondary electrons produced by the primary ionizing flux is the source of many of the observed optical emission features of the aurora. Although our theoretical understanding of the role of secondary electrons in an aurora is fairly complete, there is surprisingly little in the way of quantitative measurements to test the theoretical picture. We report here the results of a measurement of the differential secondary electron flux made in a rocket payload which also included visible and ultraviolet photometers and an ion mass spectrometer. Except for the absence of structure in the energy range 10-20 eV, the observed secondary electron spectrum is in excellent agreement with the recent theoretical predictions of Rees, Stewart, and Walker (1969), and is found to be independent of altitude. About one-half of the observed emission of the N_2^+ first negative band at 3914 A can be accounted for by secondary electron excitation. The remainder is most probably due to excitation by the primary auroral electrons, which were not measured in this experiment.

II. THE EXPERIMENT

The secondary electron spectrometer was a 180° spherical electrostatic deflection type analyzer. A complete description of the analyzer and the calibration procedure has been given by Doering et al. (1970). The geometric acceptance angle of the analyzer was a fan-shaped beam, 8° x 120°, with the larger angle oriented parallel to the symmetry axis of the rocket. The spectrum was scanned at a nominal 15 Hz rate by an exponentially decaying sawtooth voltage which varied between 800 volts and 5 volts. The resolution, $\Delta E/E$, was constant at 2.5% over the entire energy range.

Of the other instruments on the payload, only the filter photometer provided data relevant to the analysis of the secondary electron spectrum. This unit consisted of three independent interference filters--photomultiplier units sighted along the spin axis of the rocket. The three filters included the OI auroral green line at 5577 A, the (0, 0) band of the N_2^+ first negative system at 3914 A, and the (5, 2) band of the N_2 first positive system at 6685 A.

The instruments were carried aboard an Aerobee 150 rocket (NASA 4.217 UA), launched from Ft. Churchill, Manitoba, at 2241 CST on February 8, 1968. A bright auroral form was present overhead at the time of launch but quickly faded to the extent that the 5577 A photometer indicated somewhat less than 2 kR as the rocket entered the aurora (IBC I^+). The aurora was very steady except for a momentary fluctuation on the upleg of the flight (Parkinson et al., 1970 a). A peak altitude of 154.87 km was reached 213 seconds after launch. The results of the other experiments have been discussed by Opal et al. (1970), Donahue et al. (1970), Parkinson et al. (1970 b), and Dick and Fastie (1969).

III. THE SECONDARY ELECTRON SPECTRUM

Approximately one second of the telemetry record is reproduced in Figure 1. The upper trace shows the voltage sweep applied to the

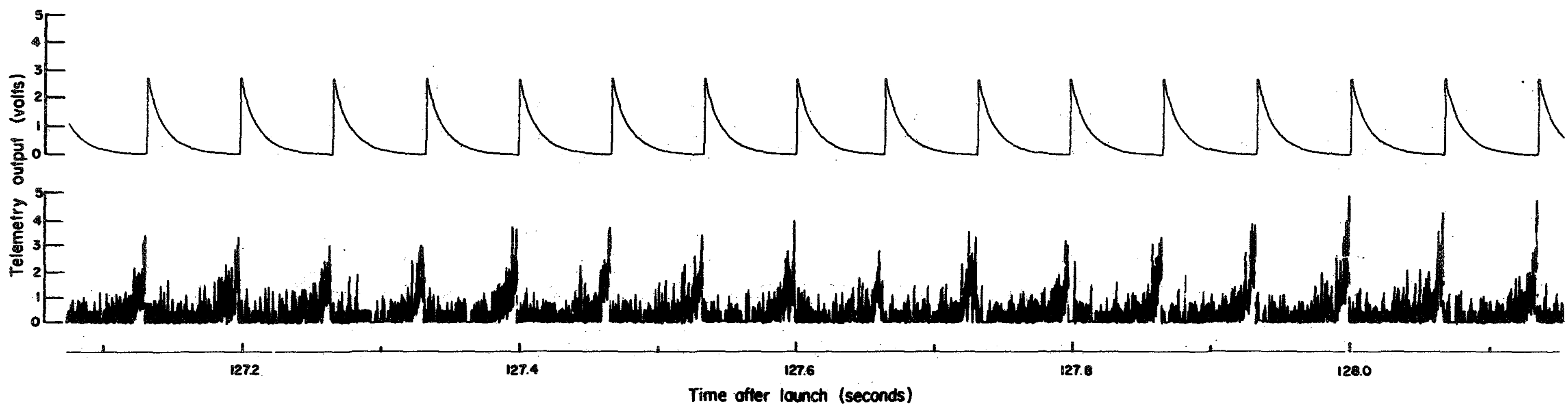

Fig. 1. A sample of the telemetry record showing the spectrometer sweep voltage (upper trace) and the output from the electron multiplier (lower trace).

ungrounded sphere of the electron spectrometer. The sweep rate is 15 Hz and the electron energy (proportional to the telemetry voltage on this channel) exponentially decreases from 800 eV to 6 eV with a time constant of 14 milliseconds. The lower trace shows the output from the electron multiplier. Note the increase in signal as the electron energy decreases with time during each sweep. The increase of the low energy electron flux in the sweeps near the end of the segment shown in Figure 1 corresponds to the auroral pulsation reported by Parkinson et al. (1970 a).

Pulses corresponding to single electrons reaching the entrance of the electron multiplier are clearly discernible on the record during the high energy portion of each sweep. Only a few of these pulses are "dark" counts. The majority are photoelectrons produced at the first dynode of the electron multiplier by auroral ultraviolet photons scattered from the interior surfaces of the electron spectrometer. This background is found to be completely independent of energy in a given sweep but does follow the auroral intensity with time. Failure to properly account for this background can lead to an erroneous interpretation of the secondary electron spectrum, as will be illustrated below.

Since the aurora was quite weak, the electron counting rates were low, and in order to obtain statistically significant spectral information, a large number of sweeps had to be summed. The data were digitized at a rate of 5 kHz, separated into individual sweeps, and then summed 90 at a time, for an average over 6 seconds. A typical summation is shown

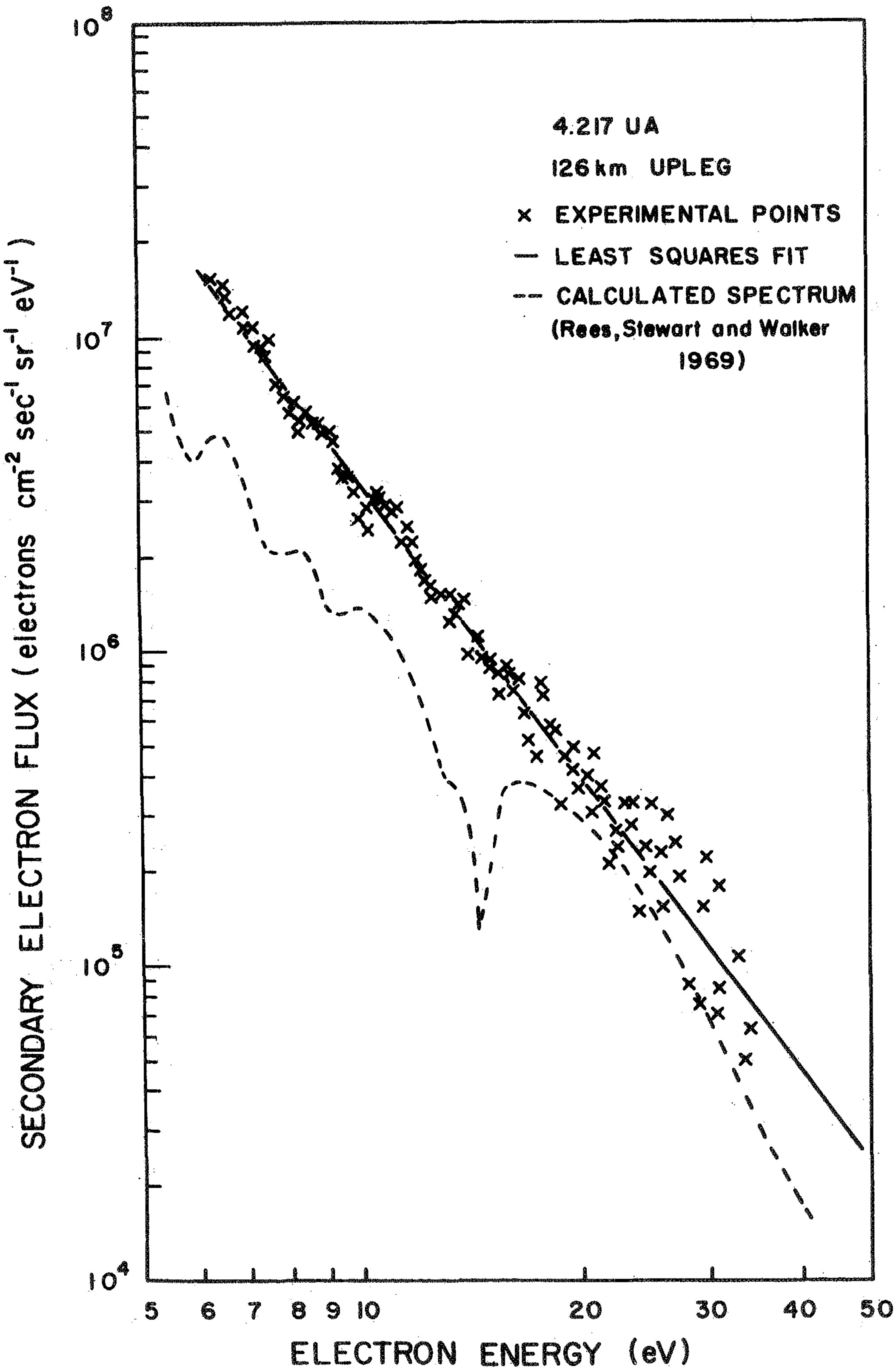

Fig. 2. A typical secondary electron spectrum obtained by summing 90 individual spectrometer sweeps. The summation over 6 seconds in time corresponds to an average over 4.5 km of altitude. The dashed curve is the calculated spectrum of Rees et al. (1969).

in Figure 2, after subtraction of background signal and conversion to electron flux per unit energy interval. In a day airglow experiment containing an identical electron spectrometer (Doering et al., 1970) the excitation rate of the N_2 second positive system calculated from the measured photoelectron flux was found to agree with the observed (0, 0) band emission at 3371 A to within 30%, so that we may adopt this figure as the uncertainty in the absolute value of the secondary electron flux. There is, however, some uncertainty in the electron energy due to the possibility of a vehicle potential (typically ~ -1 volt) which was not measured in the present experiment.

Each 6-second summation of 90 spectrometer sweeps was fit by a least-squares procedure to a power-law spectrum of the form

$$F(E) = F(E_o)(E/E_o)^{\alpha} \quad (1)$$

Here F (E) is the secondary electron flux in electrons $cm^{-2} sec^{-1} sr^{-1} eV^{-1}$ at energy E. Both $F(E_o)$ and the "spectral index" α are determined from the least-squares fit. The solid line in Figure 2 shows that the fit is quite good. In Figure 3, we plot both the spectral index α and the logarithm of $F(E_o)$, for $E_o = 10$ eV, as a function of time and altitude. Except for the outburst on the upleg noted above and a slight increase after apogee, the magnitude of the secondary electron flux appears to be fairly constant in time and altitude within the aurora. The lower border of the aurora, in terms of the secondary electrons, is at ~100 km. The spec-

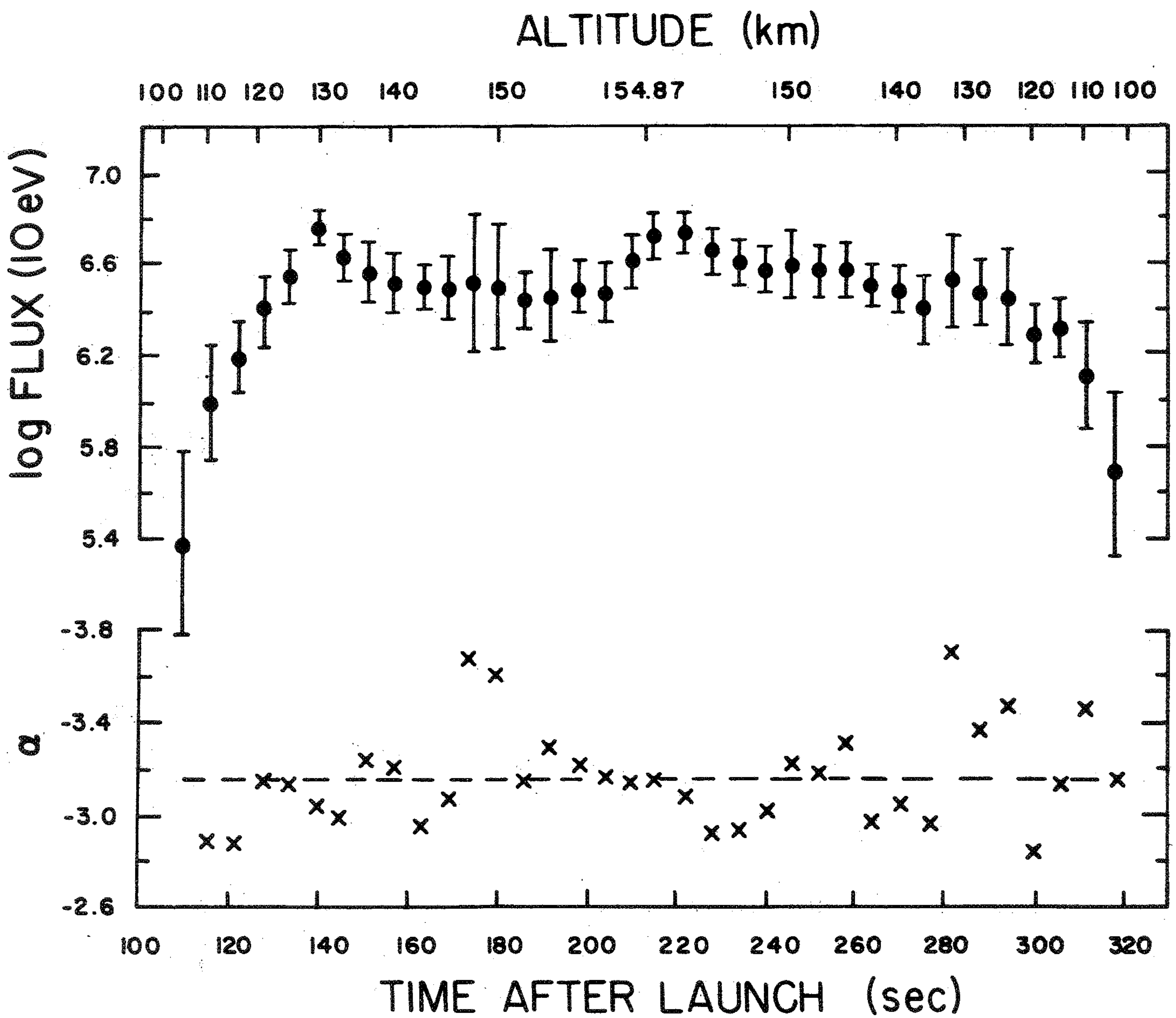

Fig. 3. The logarithm of the secondary electron flux at 10 eV (in electrons $cm^{-2} sec^{-1} sr^{-1} eV^{-1}$) and the spectral index, α, for 6-second summations of the data as determined by the least-squares fit, are shown as a function of both time and altitude. The dashed line represents the mean value of α = -3.17 ± 0.04.

tral index α was found to be completely independent of time and altitude. It has an average value = -3.17 ± 0.04, as indicated by the dashed line in Figure 3. It is amusing to note that, to within the statistical uncertainty, $-\alpha = \pi$.

Because of the low counting rates noted above, only data for electron energies less than 30 eV were used in fitting the data to a power-law spectrum. In order to extend the statistical significance of the data out to 50 eV, we took summations over 36-second intervals, corresponding to 540 individual sweeps. The results are shown in Figure 4, which contains a spectral synopsis of the entire flight. The figure demonstrates both the constancy of the spectral index and the validity of the power-law spectrum out to 50 eV.

IV. COMPARISON WITH THEORY

In Figure 2 we reproduce the calculated spectrum of secondary electrons of Rees, Stewart, and Walker (1969). Although their calculation was specifically intended to correlate with measurements at 105 km made during a different aurora, their analysis shows that the spectrum of secondary electrons is almost independent of the energy of the primary electrons and varies only slightly with altitude as the chemical composition of the upper atmosphere gradually changes. The secondary flux, of course, depends on the primary flux, but for purposes of clarity, we have not normalized the calculated value of the secondary flux to our data. Except for the absence of the predicted structure between 10 and 20 eV

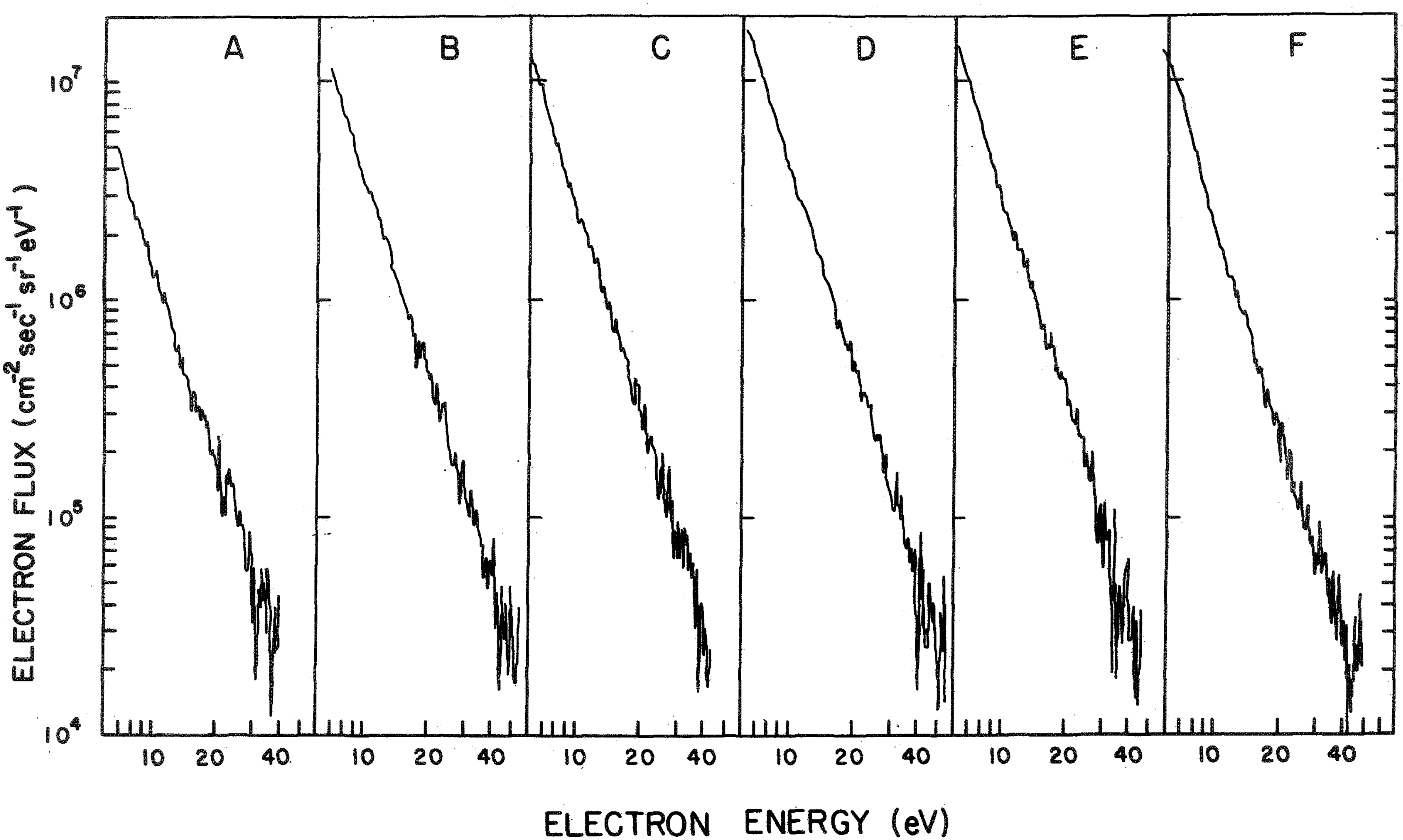

Fig. 4. Secondary electron spectra obtained by summing 540 individual sweeps, or approximately 36 seconds. The altitude range is A, 95-127 km; B, 127-147km; C, 147-155 km; D, 150-155 km (downleg); E, 133-150 km; and F, 105-133 km.

due to electron excitation of the N_2 second positive bands, the observed spectrum very closely resembles the calculated spectrum. For energies between 40 and 100 eV, where our observed flux is lost in the noise, the calculated spectrum continues to decrease with the same power law behavior.

The absence of structure in the spectrum may be instrumental, resulting from the summation of points that do not correspond to exactly the same energy. However, an analysis of the energy spread introduced by the "jitter" in the summations indicates that it is no worse than the resolution, ΔE, of the spectrometer. At an energy of 15 eV, the resolution is $\approx$ 0.4 eV, certainly not large enough to smear out the pronounced dip expected. The other possibility is that the spectrum is actually washed out by an ionospheric electric field aligned along the geomagnetic field lines. We only require that an electron lose or gain 1-2 eV in a mean-free path, so that a field of the order of 10^{-3} V m^{-1} would be sufficient to produce this effect.

There is little else in the literature to provide direct comparison with our results. Ulwick (1968) derived a secondary electron spectrum from measurements of the integrated flux (i. e., the total flux of electrons with energy greater than some given value) up to an energy of 100 eV. Heikkila and Matthews (1964) measured electron energy distributions with a low resolution detector which sampled a number of fixed energy ranges between 30 eV and 2 keV in succession. Both of these experiments give a power-law spectrum for energies less than 100 eV, with a spectral index of ≈ -2.5. A previous measurement by Doering (quoted by Pfister, 1967) gave a spectral index of -1.35, but this result is now known to be incorrect since no account was taken of the ultraviolet photoelectron background.

V. OPTICAL EMISSION FEATURES

We turn next to an examination of the correlation that exists between the measured secondary electron flux and the auroral optical emissions. Ideally, one would expect the best correlation to be obtained for the N_2 first or second positive group emissions, since excitation to the $B^3\Pi_g$ and $C^3\Pi_u$ states from the ground $X^1\Sigma_g^+$ state is possible only by electron impact. The cross sections peak only a few eV above the threshold energy (7.35 eV and 11.05 eV, respectively) and then fall off rapidly so that excitation by primary electrons is negligible. Furthermore, the emissions ($B^3\Pi_g \rightarrow A^3\Sigma_u^+$ and $C^3\Pi_u \rightarrow B^3\Pi_g$) are fully allowed and not subject to collisional quenching at auroral altitudes. Unfortunately, the data from the photometer covering the (5, 2) band of the N_2 1PG at 6685 A were contaminated with scattered moonlight during the major part of each rocket precession period, so that detailed altitude profiles could not be obtained. The data yield information about the ratio of the integrated intensities of 6685 A and 3914 A which we will discuss later.

Electron excitation of the (0, 0) band of the N_2^+ first positive system at 3914 A has been studied extensively in the laboratory (e.g., Borst and Zipf, 1970; Holland, 1967). The cross section rises gradually from a threshold at 18.8 eV to a peak near 100 eV and then gradually decreases. At 1 keV the cross section is still large enough to account for a significant contribution to 3914 A emission from excitation by primary electrons. The data from the 3914 A photometer were not contaminated by moonlight and since the aurora was fairly steady, it was possible to determine an apparent volume emission rate by differentiating the observed intensity from an overhead column with respect to altitude. This is shown by the solid line in Figure 5 for the upleg of the flight, and Figure 6 for the downleg.

Assuming that the power-law spectrum with the same spectral index is valid for secondary electrons with energies greater than 50 eV and that the distribution of secondary electrons is isotropic at all altitudes, the 3914 A volume emission rate due to secondary electrons was calculated from

$$I_s(z) = 4\pi n(z) \int_{E_{th}}^{\infty} F(E, z)\, \sigma(E)\, dE, \qquad (2)$$

where F(E, z), the flux of secondary electrons in electrons $cm^{-2} sec^{-1} sr^{-1} eV^{-1}$ at energy E and altitude z is given by Equation (1), $\sigma(E)$ is the optical cross section, and n(z) is the number density of nitrogen molecules at altitude z. A model atmosphere from the U. S. Standard Atmosphere Supplements, 1966 was chosen to best fit the time of year, geographic latitude and exospheric temperature at the time of the flight. The calculated volume emission rates and the uncertainties due to the

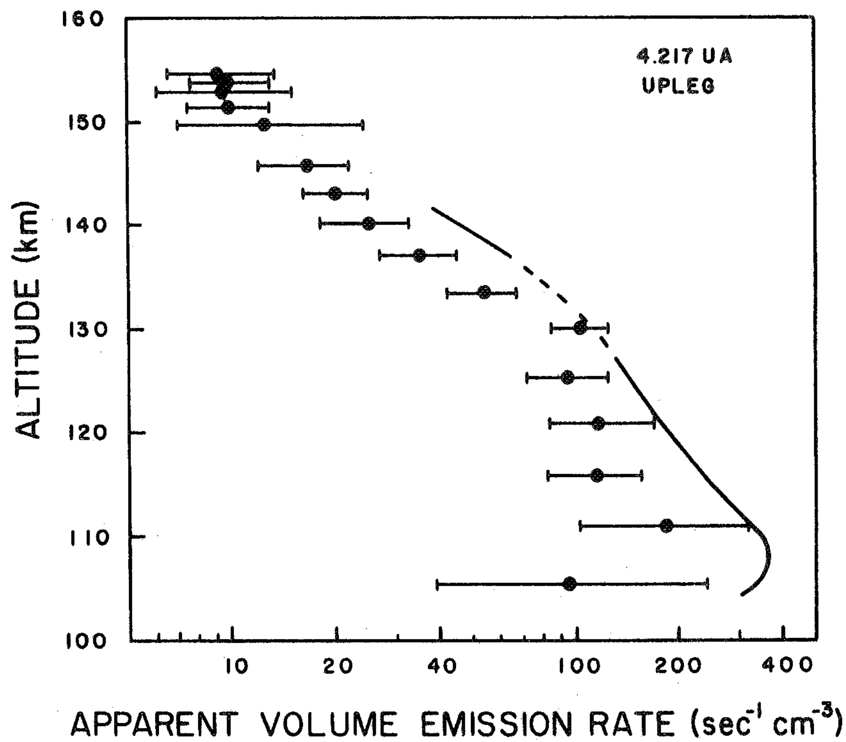

Fig. 5. Calculated and observed volume emission rates for the (0,0) first negative band of N_2^+ at 3914 A on the upleg of the flight. The solid line is the observation. The dashed part of the curve is where the momentary enhancement was subtracted to obtain the smooth altitude profile.

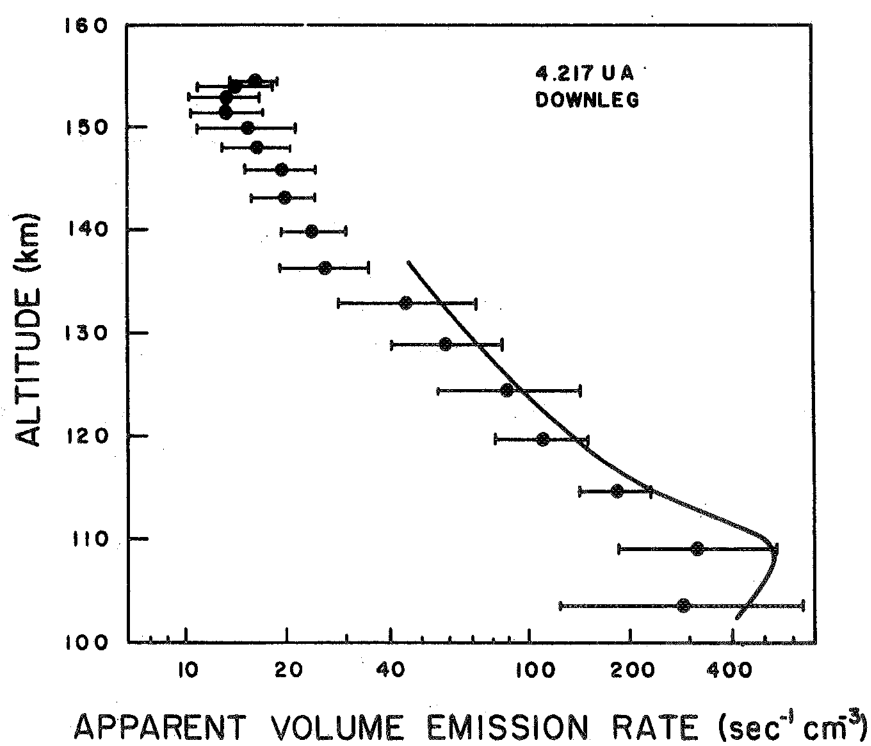

Fig. 6. Calculated and observed 3914 A volume emission rates for the downleg of the flight.

statistical uncertainty in the electron flux are also shown in Figures 5 and 6. In both cases the calculated emission rates are lower than the observed ones--by a factor of two on the upleg and about 50% less on the downleg. This difference may be real or may result from the uncertainties in the absolute flux calibration, a difference between the actual atmospheric densities and the model used in the calculations, or an erroneously derived volume emission rate due to temporal changes in brightness of the 3914 A emission. The contaminated 6685 A data is sufficient to prove that the difference is, in fact, real.

During a precession period of the rocket, the angle between the look direction of the photometer and the moon varies in a periodic manner, so that the scattered moonlight is a minimum when this angle is greatest. Near apogee, the minimum scattered light signal from the 6685 A photometer is less than the dark current, so that it is fair to assume that at lower altitudes the observed 6685 A intensity at points of maximum photometer-moon angle will be the true 6685 A emission. These occur at 88 km on upleg and 90 km on downleg. At these two points we have evaluated the ratio of the 6685 A intensity to the 3914 A intensity, which we find to be 1.66 and 1.88, respectively.

At any altitude, the ratio of the volume emission rates of these two bands can easily be calculated from

$$\frac{I_{6685}(z)}{I_{3914}(z)} = \frac{\int F(z,E)\,\sigma_{6685}(E)\,dE}{\int F(z,E)\,\sigma_{3914}(E)\,dE} \,. \tag{3}$$

The subscript notation is self-explanatory. In terms of Equation (1), this becomes

$$\frac{I_{6685}(z)}{I_{3914}(z)} = \frac{\int E^{\alpha} \cdot \sigma_{6685}(E)\, dE}{\int E^{\alpha} \cdot \sigma_{3914}(E)\, dE} . \qquad (4)$$

If the spectral index is independent of altitude, the ratio of the integrated column intensities will also be given by Equation (4). In evaluating this ratio, we used the energy dependence of the first positive cross section, which includes cascade from the second positive system, given by Stanton and St. John (1969) and the absolute cross section value given by Shemansky and Broadfoot (1970). The calculated ratio, 4.07, is larger than that observed on both legs of the flight, and implies that about one-half to two-thirds of the observed 3914 A column emission is due to excitation by primary electrons. Near the lower edge of the aurora the spectrum of primary electrons changes rapidly (Rees, 1969) and we expect that the fraction of 3914 A emission produced by the primaries is not constant with altitude. We note that the change in intensity ratio of LBH to 3914 A observed by Opal et al. (1970) on the same flight at the lower edge of the aurora may reflect such a change in the relative contribution to the excitation of 3914 A by the primary and secondary electrons.

Finally, we wish to comment on the analysis of auroral green line data by Parkinson et al. (1970 b). In calculating the contribution due to direct electron excitation of oxygen atoms, they used the 1967 data of Doering which, without the subtraction of the photoelectron background, gave a spectral index of -1.35. However, this spectrum overestimated the 3914 A intensity by a factor of 6 and hence they accordingly assumed the absolute calibration of the secondary spectrometer to be in error by this factor. As a result, they underestimate the contribution of direct excitation by secondary electrons. While this does not affect their conclusion that direct excitation plus dissociative recombination are insufficient to account for the observed 5577 A emission, it does alter significantly their estimate of the requisite cross section for the proposed dissociative excitation mechanism. Rees et al. (1969) reach the same conclusion regarding the 5577 A emission on the basis of their calculated spectrum.

ACKNOWLEDGEMENTS

We wish to acknowledge the support of the Sounding Rocket Branch at the Goddard Space Flight Center in preparing and performing this experiment. Mr. Richard Shapiro assisted in the computer analysis of the data.

This work was supported by NASA grant NGR 21-001-001.

REFERENCES

Borst, W. L. and E. C. Zipf, Cross section for electron-impact excitation of the (0, 0) first negative band of N_2^+ from threshold to 3 keV, Phys. Rev. A., 1, 834, 1970.

Dick, K. A. and W. G. Fastie, Up-down photometers for auroral profile studies, Applied Optics, 8, 2457, 1969.

Doering, J. P., W. G. Fastie, and P. D. Feldman, Photoelectron excitation of N_2 in the day airglow, J. Geophys. Res., 75, 4787, 1970.

Donahue, T. M., E. C. Zipf, and T. D. Parkinson, Ion composition and ion chemistry in an aurora, Planet. Space Sci., 18, 171, 1970.

Heikkila, W. J. and D. L. Matthews, Direct observation of low-energy electrons in the disturbed ionospheric E-region, Nature, 202, 789, 1964.

Holland, R. F., Cross sections for electron excitation of the 3914 A (0, 0) band of the N_2^+ first negative system, Los Alamos Scientific Laboratory Report LA-3783, 1967.

Opal, C. B., H. W. Moos, and W. G. Fastie, Far-ultraviolet altitude profiles and molecular oxygen densities in an aurora, J. Geophys. Res., 75, 788, 1970.

Parkinson, T. D., E. C. Zipf, and K. A. Dick, An observation in situ of an auroral pulsation, J. Geophys. Res., 75, 1334, 1970a.

Parkinson, T. D., E. C. Zipf, and T. M. Donahue, Rocket investigation of the auroral green line, Planet. Space Sci., 18, 187, 1970b.

REFERENCES

Pfister, W., Auroral investigation by means of rockets, Space Sci. Rev., 7, 642, 1967.

Rees, M. H., Auroral electrons, Space Sci. Rev., 10, 413, 1969.

Rees, M. H., A. I. Stewart, and J. C. G. Walker, Secondary electrons in aurora, Planet. Space Sci., 17, 1997, 1969.

Shemansky, D. E. and A. L. Broadfoot, Excitation of the N_2 positive and N_2^+ Meinel systems by electrons, II: Low pressure after-glow of N_2 1PG, J. Chem. Phys., to be published, 1970.

Stanton, P. N. and R. M. St. John, Electron excitation of the first positive bands of N_2 and of the first negative and Meinel bands of N_2^+, J. O. S. A., 59, 252, 1969.

Ulwick, J. C., Rocket measurements of the energy distribution of secondary electrons and electron temperature in auroras, Ann. Geophys., 24, 635, 1968.