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ROCKET INVESTIGATION OF THE AURORAL GREEN LINE

BY

T.D. PARKINSON, E.C. ZIPF AND
T.M. DONAHUE

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Rocket Investigation of the Auroral Green Line

(Planetary and Space Science)

T. D. Parkinson, E. C. Zipf and T. M. Donahue
The University of Pittsburgh
Pittsburgh, Pennsylvania 15213

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ROCKET INVESTIGATION OF THE AURORAL GREEN LINE*

T. D. PARKINSON**, E. C. ZIPF AND T. M. DONAHUE

University of Pittsburgh

Pittsburgh, Pennsylvania 15213

ABSTRACT

Results obtained from rocket borne photometers, electron energy analyzers and ion mass spectrometers show that direct excitation of atomic oxygen by auroral electrons can excite only a small fraction of the auroral green line observed. From measured ion distributions dissociative recombination of 0_2^+ is shown to contribute only weakly to the excitation of $0(^1S)$ except at high altitudes. It is proposed here that dissociative excitation of 0_2 can account for the major portion of the production of $0(^1S)$ if the cross section for the process is of order 10^{-16} cm^2. Dissociative recombination supplements this mechanism at high altitude and produces about 10 per cent of the total emission.

*This work is based on a portion of the thesis submitted by T. D. Parkinson to satisfy requirements for the Ph.D. in Physics at the University of Pittsburgh.

**Present address - Kitt Peak National Observatory, Tucson, Arizona, U.S.A.

1. INTRODUCTION

In a paper published recently Donahue et al. (1968) analyzed the results obtained from a series of sounding rocket measurements of the luminosity and electron flux in auroras. They concluded that the major source of excitation of the 2^1S term of atomic oxygen in these auroras was dissociative recombination of O_2^+ into $O(^3P)$ and $O(^1S)$ atoms. Their arguments were based on an apparent order of magnitude insufficiency in the flux of slow electrons available to excite atomic energy directly, on the large and altitude dependent cross section that would be needed for the dissociative process

$$e + O_2 \rightarrow O + O(^1S) \tag{1}$$

and on the observation that the rate of production of O_2^+ calculated for an atmospheric model in which composition and temperatures were "normal" was approximately five times the ^1S excitation rate at all altitudes. Since laboratory measurements of the rate of production of $O(^1S)$ in dissociative recombination of O_2^+ at that time indicated that twenty percent of all recombinations resulted in the formation of a ^1S atom (Zipf, 1967) the recombination mechanism seemed to be soundly supported. Furthermore, Dalgarno and Khare (1967) had shortly before shown that the energy loss of slow secondary electrons to thermal ionospheric electrons in an aurora would compete strongly with excitation of atomic oxygen. These authors also proposed that dissociative recombination should be a major source of green line excitation but used a smaller branching ratio into the ^1S channel than did Donahue et al. (1968).

Table 1: Model Atmosphere Used For Calculations

z km	n(O) cm^{-3}	n(O_2) cm^{-3}	n(N_2) cm^{-3}	T °K
100	5.8^{11}*	1.90^{12}	7.8^{12}	
102	4.6	1.25	5.2	
105	3.3	7.3^{11}	3.0	
107	2.7	5.0	2.1	
110	2.0	2.9	1.30	
113	1.45	1.80	8.1^{11}	
116	1.10	1.10	5.2	
120	8.0^{10}	6.0^{10}	3.0	310
125	5.6	3.1	1.70	337
130	3.9	1.70	9.8^{10}	368
135	2.8	9.9^{9}	6.0	402
140	2.1	5.8	3.7	440
145	1.60	3.6	2.4	480
150	1.20	2.3	1.65	521
155	9.6^{9}	1.55	1.15	560
160	7.7	1.05	8.1^{9}	598
165	6.3	7.5^{8}	5.9	633
170	5.2	5.4	4.4	665

*5.8^{11} means 5.8×10^{11}

In order to test the validity of this mechanism we incorporated a quadrupole ion mass spectrometer in the payload of a joint Johns Hopkins-Pittsburgh auroral Aerobee (NASA 4.217 UA) launched on 8 February, 1968 from Ft. Churchill. This rocket, in accordance with our standard practice, was launched into a quiet post break-up diffuse glow. In addition to the ion mass filter it was equipped with a three channel visual photometer designed to measure the overhead emission rates in the N_2^+ first negative (0-0) band at 3914Å, the OI auroral green line at 5577Å and a band of the N_2 first positive system at 6685Å. Two electron energy analyzers, an up-down photometer system isolating features near 2972Å and an ultra violet photometer completed the complement of experiments in the payload.

The results of the ion composition measurements have been reported in the paper preceding this one, (Donahue et al., 1969). They show the O_2^+ density to be a full order of magnitude smaller than expected from normal models of composition, temperature and chemistry in the region where most of the green line radiation occurred. The variation of the product of electron density and O_2^+ density with altitude does not resemble at all that of the 5577Å volume emission rate. Furthermore it now appears that the rate constant of $O(^1S)$ production in dissociative recombination of O_2^+ may be only about half as large as the value taken by Donahue et al. (1968). For these reasons it is clear that recombination contributes very little to green line production except in the high altitude portion of the aurora where - near 150 km - it might be responsible for more than half of the local excitation. We are forced, therefore, to reexamine other modes of excitation. Since, as we shall again emphasize, direct excitation of atomic oxygen by electron impact seems to remain an inadequate source, the dissociative excitation process must be advanced as the most promising candidate for the principal role in producing the green line in auroras. The prospects for this mechanism are improved by the observation that O_2^+ may take over as the main source at high altitudes, thus removing the pathological requirements on the altitude dependence of the dissociative excitation process noted by Donahue et al. (1968). In this paper we shall attempt to determine what magnitude the cross section for dissociative excitation of O_2 by electrons must assume if it is to produce the green line profiles observed in our experiments.

2. OBSERVATIONS

We shall begin by returning to the results obtained in February, 1967 (NASA 4.163 UA) which were also discussed by Donahue et al. (1968). A filter wheel photometer aboard the rocket flown then from Fort Churchill recorded the overhead brightness of the OI 5577Å line, the N_2^+ 3914Å band, the (2-0) and (1-0) first negative bands of O_2^+ at 5279Å and 5618Å and the (4-1) first positive band of N_2. An electron spectrometer obtained the energy spectrum of electrons from 2 eV (nominally) to 1000 eV between 97 km and 105 km on upleg and the total flux of electrons above 2 eV thereafter. An up-down uv photometer enabled us to make at least partial correction for small variations in luminosity caused by temporal or horizontal structure. One such variation which, according to the up-down photometer and the electron spectrometer, occured above the rocket was observed between 112 and 122 km during ascent.

The integrated emission rate of the diffuse arc remained otherwise steady at 12 kR during the up-leg. It rose to 24 kR just after apogee and then slowly decreased by a factor of about 3 as the rocket descended from 130 km to 105 km. These variations were recorded in the sum of the upward and downward looking signals obtained by the up-down photometer and seem to be correlated also with similar changes in electron flux (Fig. 3).

Local volume emission rates were obtained from the integrated overhead emission rate curves by differentiation. The results are shown in Fig. 1. Because of the presence of a temporal variation during descent the downleg curves underestimate the emission rates below 130 km and should not be regarded as valid representations of steady state emission rates.

The energy spectrum of the auroral electrons at 105 km on ascent is shown in Fig. 2. Spectra obtained at 100 km and 103 km are similar to this one. At 97 km the integrated flux was lower by a factor of 2.5.

Below 10 eV these spectra must be regarded as only poorly reflecting the actual energy distribution outside the space charge sheath around the rocket. The rocket itself has an unknown potential of several volts with respect to the plasma. The cyclotron radius of slow electrons in the terrestrial magnetic field (6 cm at 1 eV) is not small compared to the radius of the hemispherical electrodes used in the analyzer. It is difficult to see, however, in what way the effects of these perturbations could mask gross structure in the actual electron spectrum. In particular there seems to be no evidence for a depletion of flux above 6 eV corresponding to loss of electrons capable of exciting the A $^3\Sigma_u^+$ state of N_2 (Rees et al., 1967).

3. EXCITATION PROCESSES

The electron energy spectrum shown in Fig. 2 can be represented by a power law in the form

$$\phi(E) = B\ E^{-1.35} \tag{2}$$

We have used this flux to compute the rate of excitation of the 3914Å N_2^+ band at 105 km.

$$\varepsilon(3914) = 4\pi\ n(N_2) \int \phi(E)\ \sigma(3914|E)\ dE \tag{3}$$

The nitrogen density is taken from the model given in Table 1. The cross section used is that obtained by McConkey et al. (1967) and the factor of 4π implies an assumption of isotropy in electron flux above threshold for excitation of the B $^2\Sigma_u^+$ state of N_2^+. The result of this computation for $\varepsilon(3914)$ is a value 6.2 times greater than that observed and plotted in Fig. 1. We have concluded that calibration of the electron energy analyzer was in error by a large amount. There is no reason to mistrust the energy dependence above 20 eV, however. If we assume that the shape of the spectrum as observed is correct, but that the absolute scale must be adjusted to give agreement with the observed 3914Å excitation rate, the constant B in equation (2) becomes 2×10^7 electrons/cm^2 sec sr eV. At 105 km the flux of electrons with energies above 2 eV, renormalized to bring the excitation rate produced by electrons with the measured energy dependence into agreement with the observed value of ε, was 4.8×10^8 cm^{-2} sec^{-1}. The flux above 20 eV was then 1.8×10^8 cm^{-2} sec^{-1}.

The average cross section for excitation of the N_2^+ first negative (0-0) band can be calculated when the electron flux has the energy dependence of equation (2) from

$$\bar{\sigma}(3914) = \frac{\int \sigma(3914|E)\ \phi(E)\ dE}{\int \phi(E)\ dE} \tag{4}$$

The cross section calculated in this way is 1.0×10^{-17} cm^2.

If the flux above 20 eV is defined in terms of

$$\phi_T(\ > 20\ \text{eV}) = 4\pi \int_{20} \phi(E)\ dE \tag{5}$$

then it follows from equations (3) and (4) that

$$\phi_T(\ > 20\ \text{eV}) = \varepsilon(3914)/n(N_2)\ \bar{\sigma}. \tag{6}$$

The efficiency of 3914Å band excitation, $\varepsilon(3914)/n(N_2)$ has been calculated for all altitudes throughout the flight. Then the total flux above 20 eV has been computed under the assumption that $\bar{\sigma}$ (which is to say the energy dependence of the flux) remained constant at 10^{-17} cm^2. In computing efficiencies nitrogen densities were taken from a model developed by Zipf (1967) from optical measurements. The densities in this model over the range of altitudes of interest are very similar to those which would be obtained from other models such as those of Bates (1959) and Walker (1965). Below 120 km the model was smoothed to one developed by Anderson and Francis (1966). Although the Jacchia (1965) model exospheric temperature during the 1968 experiment was 1087°K, no appreciable difference in model densities below 170 km are predicted between the 1967 and 1968 experiments.

The total flux above 20 eV computed from equation (6) is plotted in Fig. 3. This flux when multiplied by 10^{-17} cm^2 is simply a measure of the excitation efficiency (probability of excitation per target particle) without any assumptions concerning the electron flux or energy spectrum. $\phi_T(>20$ eV) is compared to the figure with the measured (but normalized) electron flux above 2 eV. Between 104 km and 125 km on the upleg $\phi_T(>20$ eV), or the efficiency, remains essentially constant - as does the ratio to the measured total flux. Near apogee the efficiency as well as its ratio to the measured flux apparently increases and during the downleg to 125 km both remain high. $\phi_T(>20$ eV)/$\phi_T(>$ eV) is about three times as large above 130 km on descent as it was at 105 km during ascent. Below 130 km on the downleg the apparent efficiency drops more rapidly than the observed flux to a level which is roughly in agreement with that obtained for the ratio of these two quantities at low altitude during ascent. However, the general weakening of the aurora during this period renders our method of computing ε and hence $\phi_T(>20$ eV) suspect. As was mentioned above the computed values for these two quantities are probably too low. Nevertheless, indications are that the flux is more effective by about a factor of 3 in exciting the (0-0) first negative band above 130 km than it is near 105 km. This might be ascribed to an increase in the flux component below 20 eV at low altitude except that the integrated measured flux above 2 eV was not observed to increase below 130 km. The high values of $\phi_T(>20)/\phi_T(>2)$ found between 150 km and 130 km on downleg instead were accompanied by a measured flux about 60 percent greater than that observed at low altitude during ascent. It is this enhanced flux which appears to be more efficient above 20 eV.

The efficiency for green line excitation by the assumed process

$$e + O(^3P) \rightarrow O(^1S) + e \qquad (7)$$

was calculated for the upleg of this flight by an evaluation of the quantity

$$P(5577|O) = \varepsilon(5577)/Qn(O) \qquad (8)$$

The quenching factor Q was evaluated with the use of a rate constant of 2.1×10^{-13} cm^3 sec^{-1} (Zipf, 1967) for collisions between $O(^1S)$ and O_2. Q was 0.96 at 110 km, 0.91 at 105 km and 0.81 at 101 km. The excitation efficiency was also computed from the observed (but renormalized) electron differential energy spectrum

$$P(5577|O) = 4\pi \int \phi(E)\, \sigma(E)\, dE \qquad (9)$$

where the integration range was between threshold and 54 eV. The cross section for excitation of $O(^1S)$ was that calculated by Henry et al. (1968). The observed and computed efficiencies are compared in Fig. 4. Only if the measured flux were deficient between 2 eV and 20 eV by a factor of varying between 100 and 30 could these two results be brought into general agreement. Alternatively an increase in the atomic oxygen content of the model by a factor of varying between 100 and 30 would accomplish the same result.

It was this difficulty which led Donahue et al. (1968) to consider processes involving collisions between high energy electrons and O_2 as sources for ^1S excitation. The process which they considered most promising was ionization of N_2, O and O_2 terminating in the production of O_2^+. Subsequent dissociative recombination of O_2^+ was to produce the $O(^1S)$ atoms observed. However, the ion mass spectrometer data now have eliminated O_2^+ as a source except at high altitudes. We shall, therefore, reexamine the alternative high energy channel represented by equation (1).

In Figs. 5 - 7 we show the average cross section for this process evaluated from the expression

$$\bar{\sigma}(5577|O_2) = \frac{\varepsilon(5577)}{Qn(O_2)\phi_T(> 20 \text{ eV})} \tag{10}$$

The total flux is that computed from the efficiency for production of the (0-0) first negative N_2^+ band. Hence this average cross section can be regarded as measuring the ratio of the efficiencies for production of $O(^1S)$ from O_2 and the N_2^+ 3914Å band from N_2. This ratio is just $\bar{\sigma}(5577)$ divided by 10^{-17} cm^2. As illustrated in Figs. 5 - 7 the average cross section has been computed for both legs of the 1967 experiment and for the upleg in 1968. The trend in all three cases is almost identical. A value of 10^{-16} cm^2 (or an efficiency ratio of 10) almost constant with altitude is called for up to about 130 km. Above 130 km the relative efficiency must increase to about 30 (3×10^{-16} cm^2) at 145 km if this is the sole important channel for green line production.

It was this high altitude increase which led Donahue et al. (1968) to reject this mechanism in favor of dissociative recombination. Now, on the other hand, we know that dissociative recombination can contribute insignificantly to the excitation of ^1S at low altitudes but that its potential importance becomes significant above 130 km. Shown in Fig. 7 is the O_2^+ density, the total ion density Σn_i^+ and the product

$\Sigma n_i^+ n(O_2^+)$ measured during the up-leg of the 1968 flight. Also shown in the figure is the contribution dissociative recombination must make to the excitation rate $\epsilon(5577)$ if the cross section $\bar{\sigma}(5577|O_2)$ - or the efficiency ratio for the dissociative excitation process - is to remain constant. It is clear that if the rate constant for production of $O(^1S)$ in dissociative recombination of O_2^+ is of the order of 10^{-8} cm^3 sec^{-1} that a major fraction of the green line production above 130 km will come from O_2^+ recombination. Since the most recent measurements indicate a value of the order of 2×10^{-8} cm^3 sec^{-1} for this rate constant at 300°K (Zipf, 1969) the requirements are reasonable if the electron temperature is elevated to values of 1000°K or higher. Because of the inaccuracy in determining the gradient of the overhead brightness curves to determine the emission rate and the unknown recombination branching ratio into the $O(^1S)$ term at high electron temperatures it would not be worthwhile to try to assess the relative contributions of the two processes at high altitude.

In Figs. 5 and 6 are shown the average cross sections for excitation of the O_2^+ (1-0) and (2-0) first negative bands in the 1967 aurora. The similarity in the behavior of these curves to $\bar{\sigma}(5577|O_2)$ at low altitude and the absence of a high altitude increase such as occurs in $\bar{\sigma}(5577)$ suggests that it makes sense to regard O_2 as the source of the O_2^+ and $O(^1S)$ radiation except for a high altitude component in the excitation of the green line.

If the postulated recombination contribution to the green line is removed the ratio of the integrated 5577Å to 3914Å emission rates is about 1.7. If the dissociative excitation process is the source of the residual ^1S excitation then it occurs with a frequency about 10 percent of ionization of N_2 or about 7 percent of the total atmospheric ionization rate. Its efficiency, however, would be about half that for ionization of O_2. Clearly this is a stiff requirement, but we see no reasonable alternative to this mechanism. An average cross section for all collisional dissociative processes leading to the ^1S level of O of the order of 10^{-16} cm^2 will, however, be required. A laboratory measurement is clearly needed.

4. DISCUSSION

The proposal here that dissociative excitation of O_2 contributes a major part of the $O(^1S)$ in an aurora while dissociative recombination produces about ten percent of the total mainly at high altitude seems to be reconcilable with most reported features of green line radiation in auroras. Donahue et al. (1968) showed that some results reported by Evans and Vallance Jones (1965) for the phase shifts between 5577Å and 3914Å emissions in flaming auroras could be explained in terms of the time constants characteristic of dissociative recombination. There are, however, many other cases of fluctuations reported in the literature indicating that the delay is associated with the radiative lifetime of $O(^1S)$ and that direct production of the ^1S state by electrons is the primary source of excitation. We have recently obtained further data supporting these conclusions (Parkinson et al., 1969). It may be that rapid changes in vertical distribution associated with flaming auroras invalidates the approach used by Donahue et al., (1968) to explain the data of Evans and Vallance Jones (1965).

It remains to be seen whether the dual source mechanism proposed here can account for the observations of Romick and Belon (1967) that the ratio of 5577Å brightness increases toward the center of the stable arcs. Since the fraction of the total ion production going to produce O_2^+ is height dependent and since diffusive loss of ions may be important near the borders of arcs there does seem to be a possibility that a varying ratio of the two sources of $O(^1S)$ production may explain the phenomenon reported.

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FIGURE CAPTIONS

Fig. 1. Volume emission rates observed during flight 4.163 UA, Ft. Churchill, 1967.

Fig. 2. Electron energy spectrum measured on flight 4.163 UA, 1967 at 105 km on upleg. The scale is that appropriate to the pre-flight calibration.

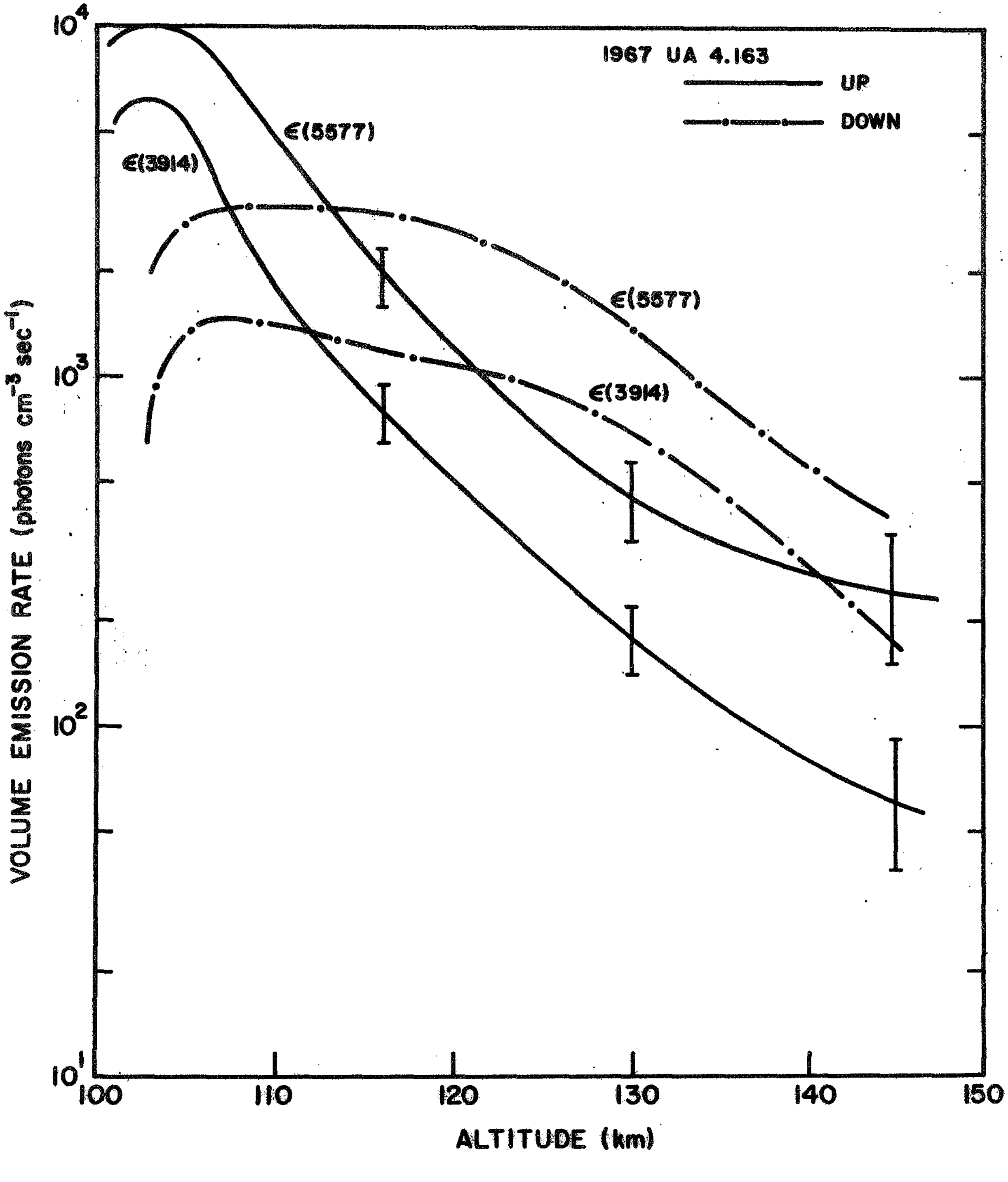
Fig. 3. The total electron fluxes are shown for the 1967 experiment. The solid line is the signal which is believed to be the total flux of electrons with energy greater than about 2 eV. As plotted it is a factor of 6.2 less than that for which it was calibrated. The X's show the flux with energy greater than 20 eV calculated from the λ3914 signal.

Fig. 4. Excitation efficiency as observed in the upleg of the 1967 experiment and as calculated for a direct impact excitation model using the measured electron flux and the cross section of Henry et al. (1968).

Fig. 5. Average excitation cross sections calculated for the upleg of the 1967 experiment. Of importance is the relative increase of $\bar{\sigma}$ for dissociation relative to that for the first negative system. The errors at 145 km are expected to be inside the limits shown.

Fig. 6. Cross sections calculated for downleg of the 1967 experiment, (flight 4.163 UA).

Fig. 7. Volume emission rates observed by the 1968 experiment (flight 4.217 UA) on the up leg. Also shown is the electron density and O_2^+ ion density. The cross section needed for dissociative excitation of the $O(^1S)$ state is also plotted. The shaded area shows that portion of the green line due to dissociative recombination of O_2^+.



1967 UA 4.163
UP
DOWN
ϵ(5577)
ϵ(3914)
ϵ(5577)
ϵ(3914)
10^4
10^3
10^2
10^1
VOLUME EMISSION RATE (photons cm^-3 sec^-1)
100
110
120
130
140
150
ALTITUDE (km)

Figure 1

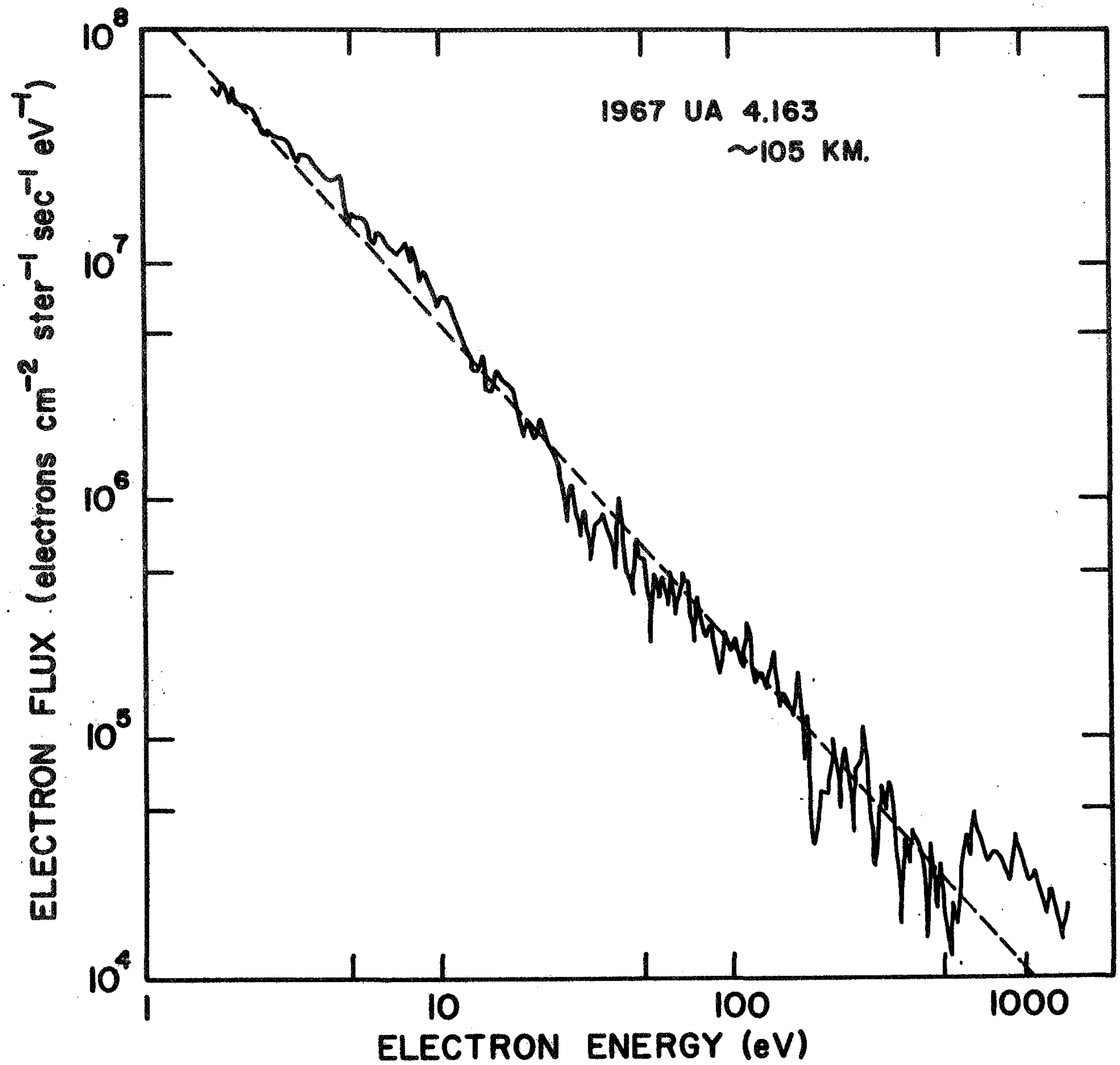
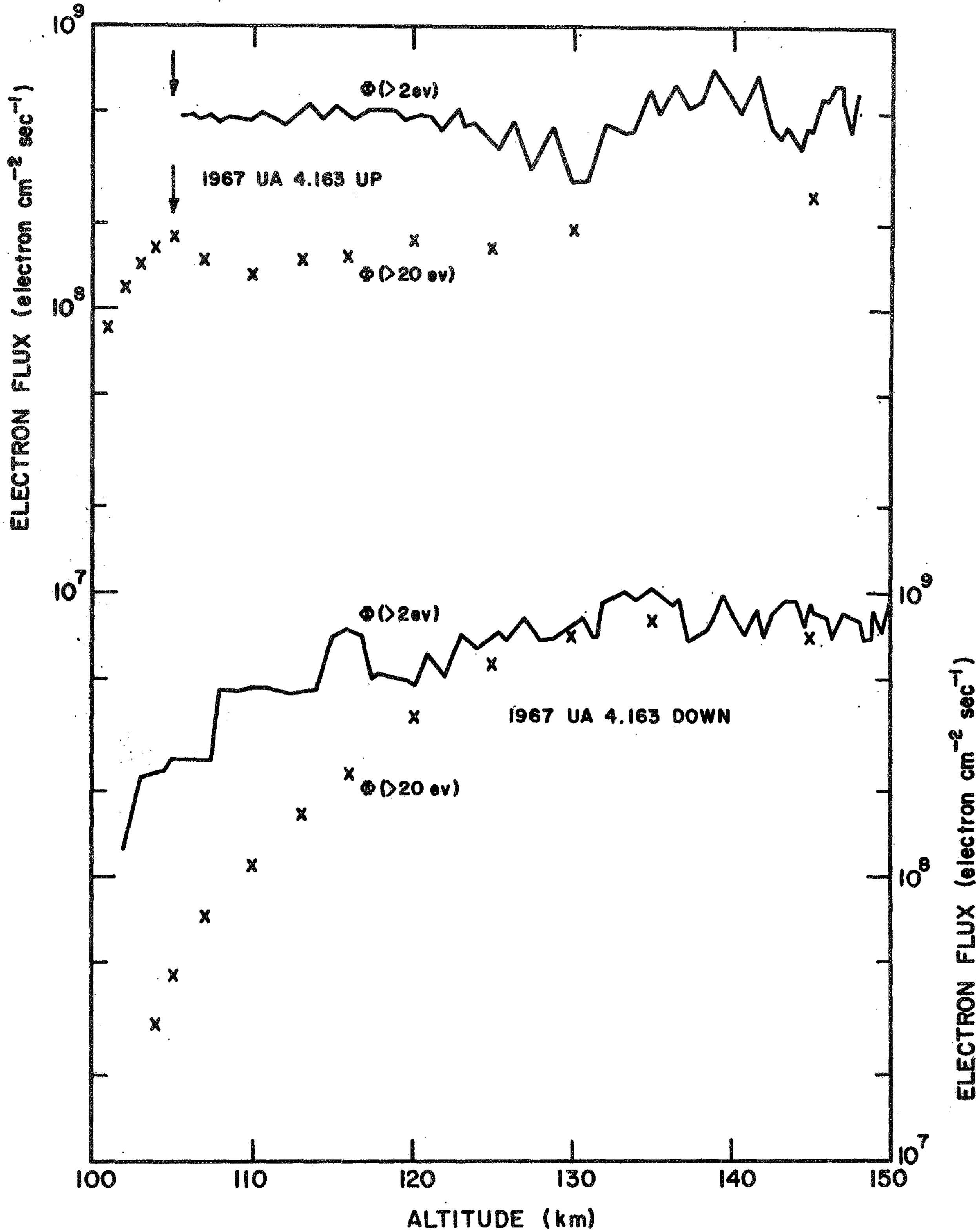
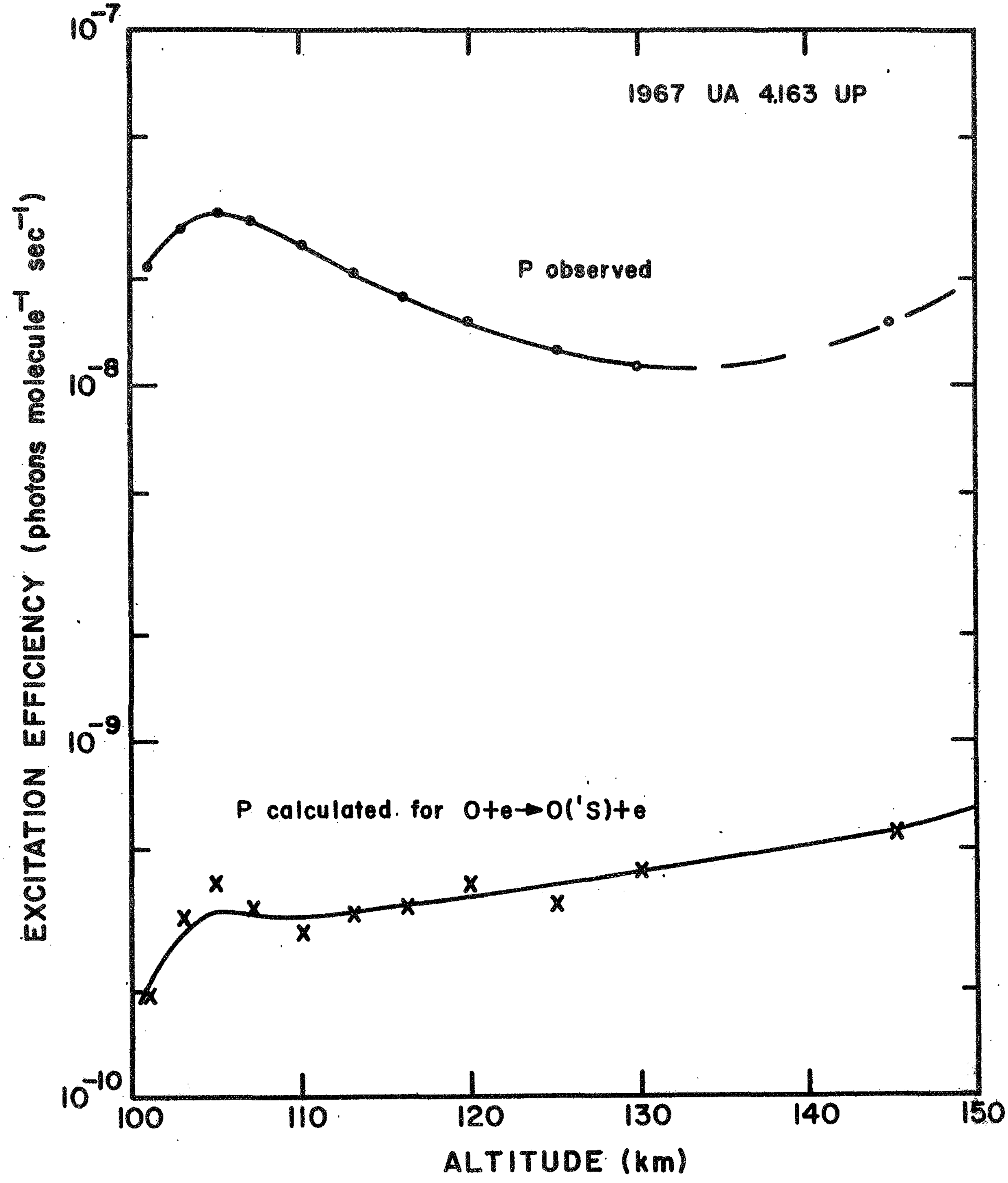

1967 UA 4.163
~105 KM.
ELECTRON FLUX (electrons cm^{-2} ster^{-1} sec^{-1} eV^{-1})
ELECTRON ENERGY (eV)
10^8
10^7
10^6
10^5
10^4
1
10
100
1000

Figure 2



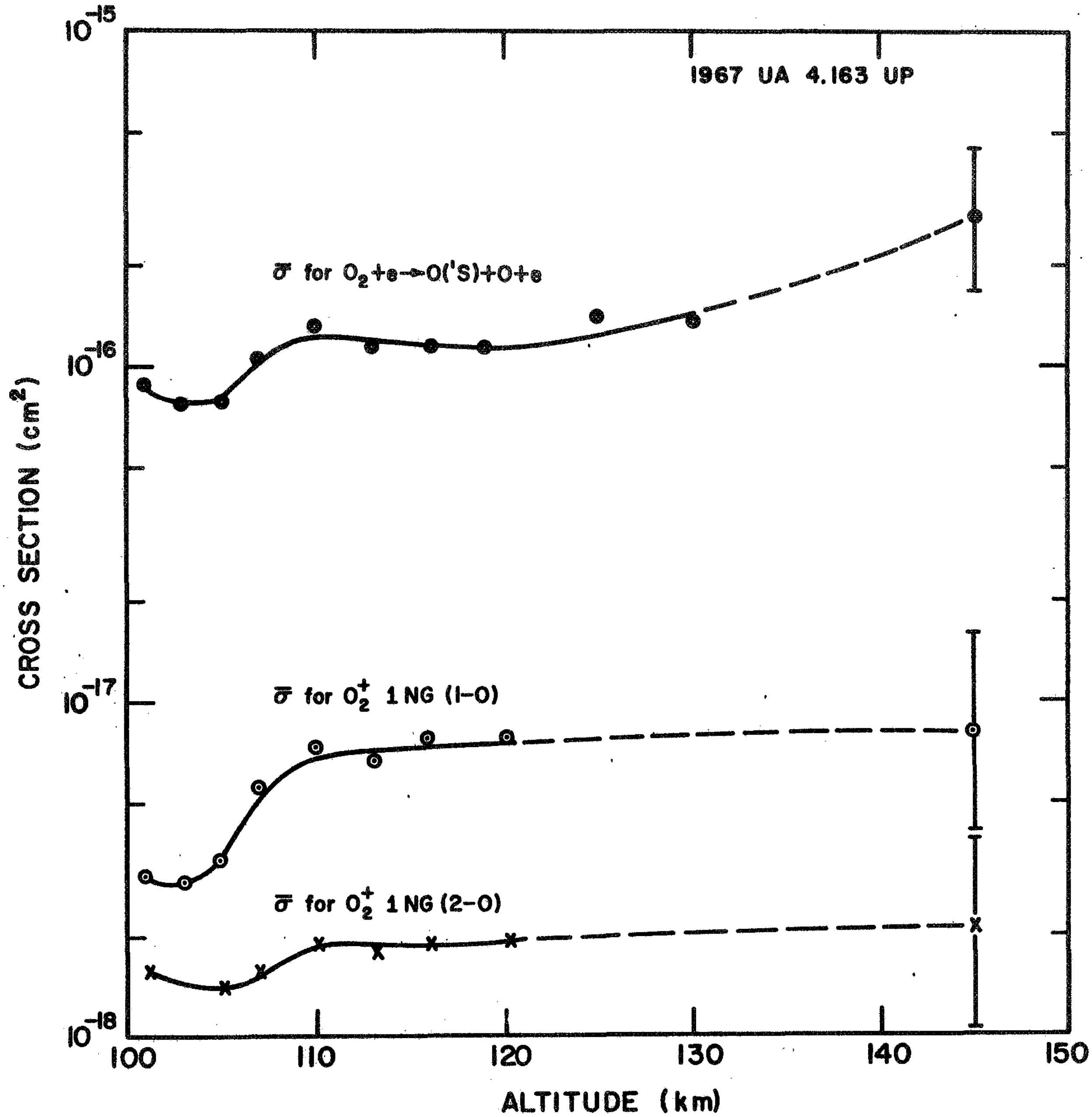
Φ(>2ev)
1967 UA 4.163 UP
Φ(>20 ev)
Φ(>2ev)
1967 UA 4.163 DOWN
Φ(>20 ev)
ELECTRON FLUX (electron cm^{-2} sec^{-1})
ELECTRON FLUX (electron cm^{-2} sec^{-1})
ALTITUDE (km)
10^9
10^8
10^7
10^9
10^8
10^7
100
110
120
130
140
150

Figure 3



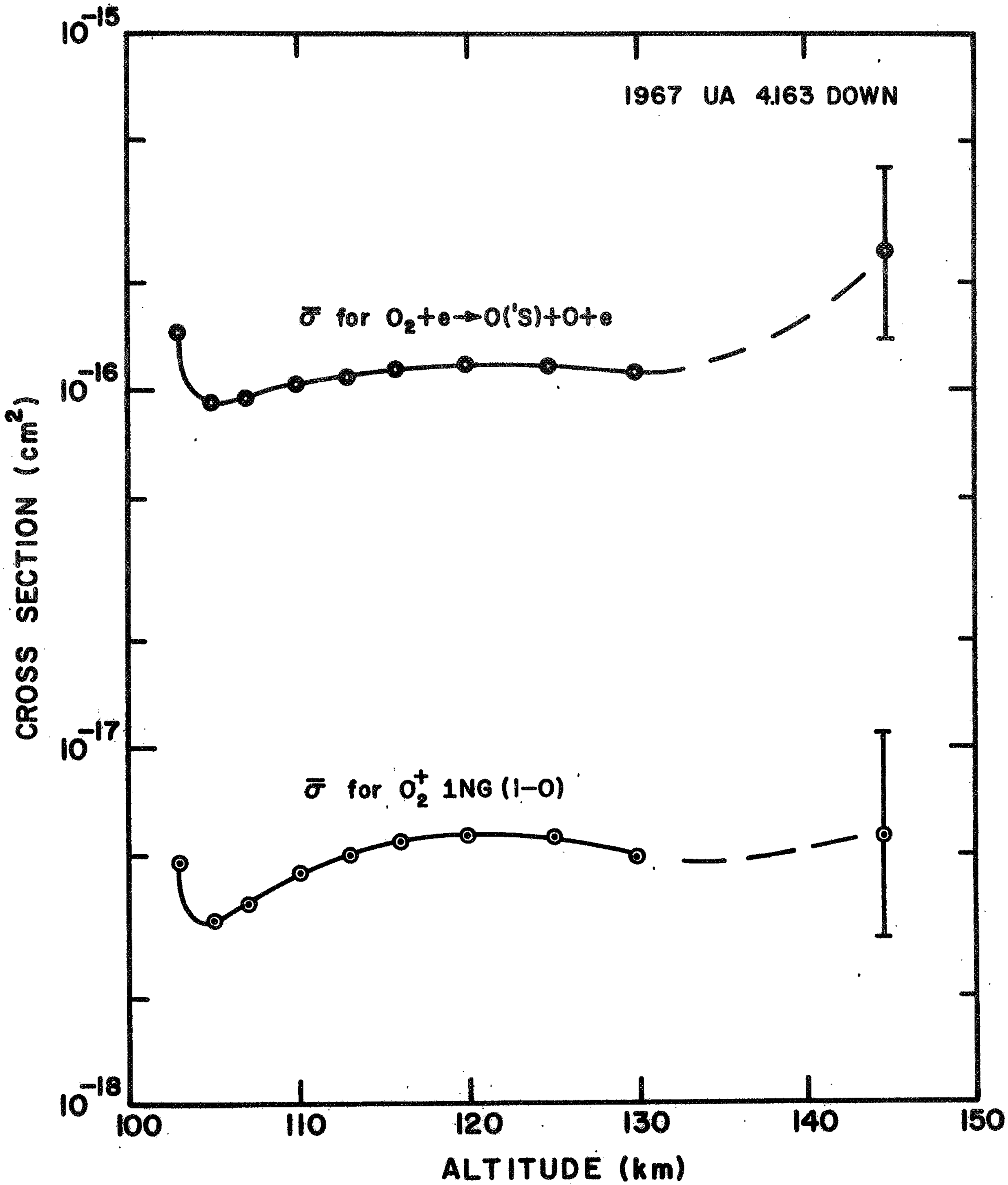
1967 UA 4.163 UP
P observed
P calculated for O+e→O('S)+e
EXCITATION EFFICIENCY (photons molecule⁻¹ sec⁻¹)
ALTITUDE (km)
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
100
110
120
130
140
150

Figure 4



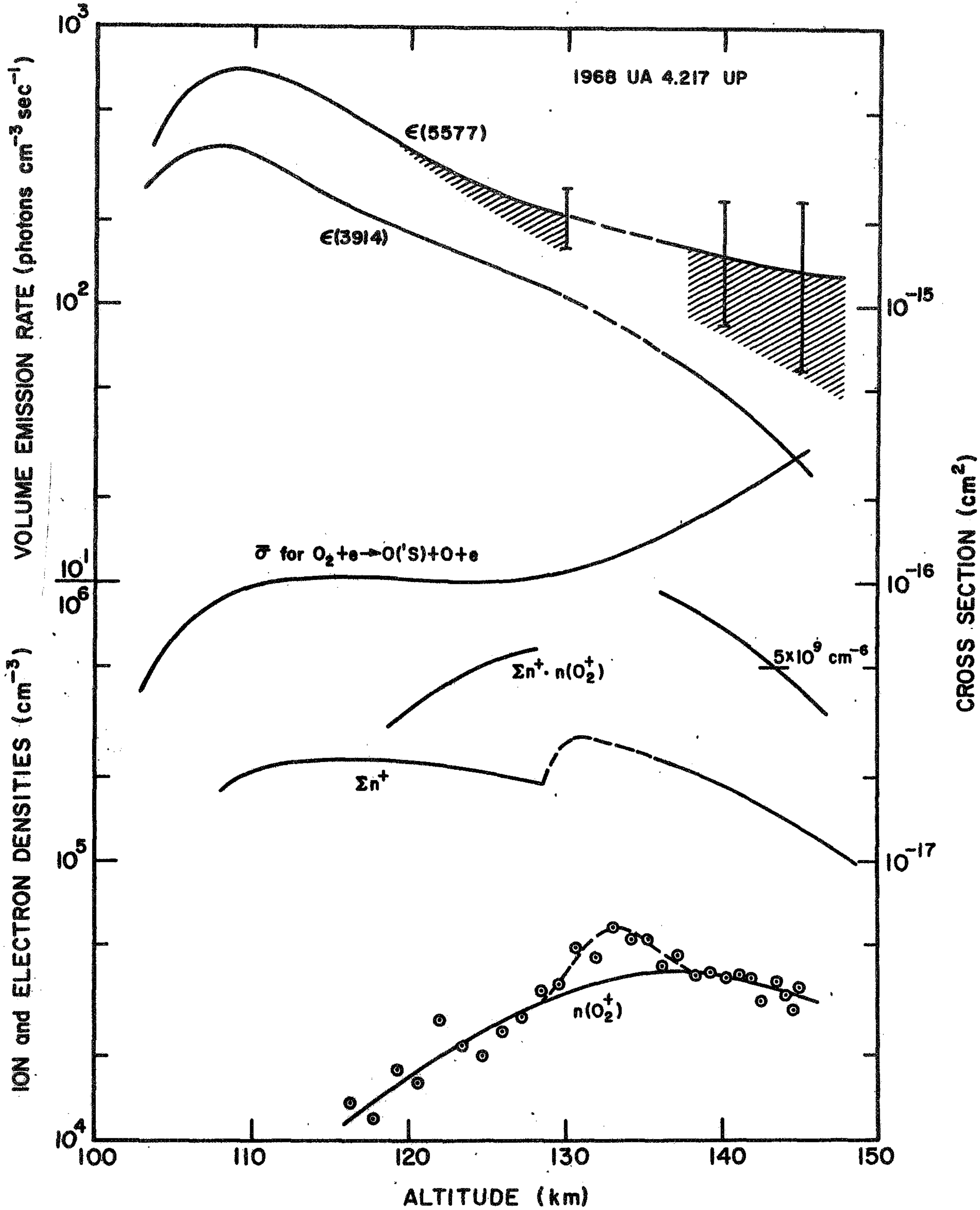
1967 UA 4.163 UP
$\bar{\sigma}$ for $O_2+e \rightarrow O(^1S)+O+e$
$\bar{\sigma}$ for O_2^+ 1 NG (1-0)
$\bar{\sigma}$ for O_2^+ 1 NG (2-0)
CROSS SECTION (cm^2)
ALTITUDE (km)
10^{-15}
10^{-16}
10^{-17}
10^{-18}
100
110
120
130
140
150

Figure 5



1967 UA 4.163 DOWN
$\bar{\sigma}$ for $O_2+e \rightarrow O(^1S)+O+e$
$\bar{\sigma}$ for O_2^+ 1NG (1–0)
CROSS SECTION (cm^2)
10^{-15}
10^{-16}
10^{-17}
10^{-18}
100
110
120
130
140
150
ALTITUDE (km)

Figure 6



1968 UA 4.217 UP
ε(5577)
ε(3914)
σ for O2+e→O(1S)+O+e
Σn+· n(O2+)
5×10^9 cm^-6
Σn+
n(O2+)
VOLUME EMISSION RATE (photons cm^-3 sec^-1)
ION and ELECTRON DENSITIES (cm^-3)
CROSS SECTION (cm^2)
ALTITUDE (km)
10^3
10^2
10^1
10^6
10^5
10^4
10^-15
10^-16
10^-17
100
110
120
130
140
150

Figure 7