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(Final Report)

INVESTIGATION OF TECHNIQUES FOR THE REMOVAL OF ELECTRONS IN THE UPPER ATMOSPHERE

December 1, 1961 through December 31, 1962

Contract No. AF 19(628)-316
ARF Project A204

Prepared by

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FOREWORD

This is Report No. ARF-A204-3, Final Report, of ARF Project A204, Contract No. AF 19(628)-316, entitled "Investigation of Techniques for the Removal of Electrons in the Upper Atmosphere". The report covers the period from December 1, 1961 through December 31, 1962. The technical monitor on this project was Samuel Horowitz.

The project leader and chief contributor at Armour Research Foundation was Robert D. Sears. Other contributors were R. Nasoni and R. F. Tooper. The major portion of the contract time was devoted to an investigation of the dynamical behavior of normal D-region electron loss processes and electron energy loss processes as they would affect initiation of loss of electrons in the D region by artificial means. To this end one must attempt to describe the competition between electron loss and electron energy loss as a function of the initial electron energy for both abnormal and normal condition. The body of this report is concerned with normal D and lower E region conditions under rather restrictive assumptions. Further development of a computer technique for obtaining D region electron densities as a function of height from multiple frequency riometer data was carried out and reported in Quarterly Reports 1 and 2. (ARF-A204-1 and ARF-A204-2). It would be desirable to extend this work to less rigid conditions and to include introduction of man made or solar disturbances.

This report has been submitted for publication to the Journal of Geophysical Research.

Respectfully submitted,

ARMOUR RESEARCH FOUNDATION
of Illinois Institute of Technology

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APPROVED BY:

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2/11/63

Contribution of Energetic Photoelectrons to D Region Non-equilibrium Electron Temperatures

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Abstract

Electron equilibrium energy in the D and lower E region of the ionosphere is calculated from a relationship between electron energy loss and attachment characteristic times. It is shown that solar photodetachment of electrons from O_2^- ions, which is the major short term ionization source between 50 and 90 km, is a source of energetic electrons of 2.9 ev mean energy. Thus competition between energy loss by rotational excitation of molecules and dissociative attachment to oxygen will exist as the most probable processes for 3 ev electrons. Approximate conditions are defined which allow calculation of maximum mean electron energy at equilibrium for the undisturbed or slightly disturbed daytime ionosphere. Comparison of these maximum values with a measured electron energy of 0.15 ev at 40 km shows agreement within a factor of 2, which may be accounted for by the disturbed condition of the ionosphere during the measurement. The range of maximum permissible electron energies lie between 1.2 times ambient at 30 km to 42 times ambient (0.74 ev) at 90 km. A method is outlined whereby one parameter among the set, equilibrium electron energy, energy loss characteristic time, or electron removal characteristic time can be determined if the other two can be found experimentally and if the mean source energy of the electrons is known. Thus radio measurement techniques such as the Luxemburg effect or rocket probes can be used to relate temperature measurements and electron density measurements through a reaction model based upon [illegible]

INTRODUCTION

Many areas of ionospheric physics and engineering implicity assume that the components of the ionospheric plasma are in thermodynamic equilibrium with each other, and with the numerous energy input sources. A further assumption which has recently been shown erroneous in part (Rumi, 1962, Spencer et al 1962) is that the electron temperature of the ionosphere is equal to the neutral temperature. Of course a treatment of the F region or exosphere as a plasma would not be prone to this error, but many treatments of the D and E regions from a reaction model viewpoint have implicitly assumed this. Furthermore, treatments of the electromagnetic propagation properties of the D and E regions neglect in many cases the energy loss processes of the electron gas and usually assume temperature equilibrium between the electron and neutral plasma components.

It is the purpose of this paper to describe the energy sources for electrons in the D and lower E regions and the subsequent loss of this energy in the production of an electron gas at or near thermal equilibrium. Competition between energy loss and dissociative attachment to oxygen molecules is shown to take place for those electrons photodetached from 0_2^- because the mean initial electron energy is not thermal but near 3 ev. As the electron suffers collisions, energy loss takes place primarily by rotational excitation of molecules even though the majority of collisions which affect electromagnetic propagation are elastic. The primary sources of electrons in the D and E regions are photodetachment and photoionization and it is shown that the contribution of initially energetic photoelectrons to the chemical reaction effects and to the equilibration of the electron gas temperature will increase with increasing altitude.

In this paper, it is assumed that the gas is weakly ionized such that the following conditions hold: electron-ion recombination is negligible compared with other electron losses, and electron-ion coulomb interactions may be neglected. Two classes of processes can be distinguished: fast processes involving electron attachment, detachment, collisional energy loss by both elastic and inelastic processes, and positive ion-atom interchange, and the slow processes involving electron-ion recombination and ion-ion recombination. It is assumed that no disturbances exist which would violate the conditions assumed. Thus strong solar flares cannot be included if electron densities in the D region are increased above about 10^4 cm^{-3}. Although these conditions may seem too restrictive to allow useful description of an effect which is subsequently shown to be continuous during the daytime, one is hereby allowed to describe the competitive energy relaxation vs. energetic electron loss processes without concern for the long term effects which these may have had upon ionospheric composition. One also can obtain limits on mean equilibrium electron energy by examination of relative time constants for the competing processes rather than by attempting a complete solution of a Boltzmann type equation for inelastic energy loss processes, for which the cross sections at various energies are not well known experimentally. The energy distribution for the major D region electron source, namely photodetachment from O_2^-, as obtained from experimental data is found to be nearly a Gaussian distribution with an average energy of 2.9 ev. Relative time constants for competing processes are compared, and it is found for 3-eV electrons that rotational excitation energy loss is about 100 times faster than that of elastic collisions and is the major cause of electron energy loss. Moreover, the dissociative attachment characteristic time at all altitudes between 30 and 100 km is a factor of 3 to 4 less efficient for removing electrons than the rotational excitation process is in decreasing their energy. Thus simple comparison of these times indicates a minimum attachment rate of at least 2 percent of all electrons produced by photodetachment before they relax to e^{-1} of their original energy. Comparison of characteristic times in a many collision approximation to plasmas undergoing ionization and electron removal for the equilibrium temperature of the electron gas indicates that thermal equilibrium with the ambient gas may not be reached, and the maximum possible electron temperature as a function of altitude is found consistent with the validity of use of the Chapman and Cowling (1960) derived approximation.

Finally, it is shown that although the energetic electrons represent a large source of potential energy available to endothermic electron reactions, the usual reaction chemistry of the D region is not significantly modified. The main effect is simply addition of the dissociative attachment source of atomic oxygen to the already large source present due to photodissociation. Consideration of possible endothermic electron reactions with normal ionospheric species indicates no unusual species are likely to be formed.

PRODUCTION OF ENERGETIC ELECTRONS BY PHOTO PROCESSES

The major source of electrons in the ionosphere is ionization by solar photons of neutral and negative ion species. If slow electron loss processes in the D and lower E regions are accounted for, one can define an effective ionization source function independently of theoretical models for ionization of specific constituents of the atmosphere by particular spectral portions of the incident flux. Obviously these approaches must produce the same source terms, but the first allows ready comparison of theoretically derived photoionization sources with the total source derived from overall ionization and loss processes. Table I presents the results of such a comparison with the derived photo-ionization source function presented at various heights. Coefficients for the calculations from Webber (1962) and Nicolet and Aiken's (1960) values of N_eN_+ resulting from the Lyman-alpha ionization of NO in the D region are taken and extended to 90 and 100 km. Figure 1 illustrates the relative strengths of the two photo-electron sources, photo-detachment and photo-ionization. It is readily apparent that the latter sources are major contributors to ionization above 50 km. This is of interest since these two sources are more likely to produce energetic electrons than the major electron source (collisional detachment) below 50 km. Photo-detachment which is the major electron source between 50 and 90 km takes place when the solar flux removes an electron from the ground or excited state of O_2^-, the energy thresholds for which are 0.46 and 0.15 eV. respectively. The solar spectrum peaks well above these energies, so it is qualitatively likely that energetic electrons would be produced from this process.

The electron energy spectrum was obtained by multiplying the experimental values of photo-detachment cross section obtained by Burch, Smith, and Branscomb (1958) and expressed theoretically by Geltmann (1958) by the solar photon flux spectrum derived from the measured energy spectrum (Johnson, 1961) in the region 2200 A to 12,000 A. A suitable adjustment to account for a threshold energy of 0.15 eV was made and the electron energy distribution was found to be nearly Gaussian with a peak at 2.9 eV. Figure 2 plotted on special Gaussian graph paper illustrates the Gaussian characteristic of the electron energy distribution.

RELATIVE RELAXATION TIMES FOR COMPETING PROCESSES

The characteristic relaxation times associated with the fast processes (elastic collisions, inelastic rotational excitation, and 2-body and 3-body attachment) are compared with one another in the altitude range 30 to 100 km. A physical limit to the speed of a reaction is provided by the collision frequency or characteristic time for elastic collisions of electrons with neutral particles and is a well known function in this altitude range. The characteristic times of ionospheric slow processes are about seven orders of magnitude greater than those of the fast processes. Energy loss by elastic collision is usually considered to take place with a fractional energy loss per collision of 2 m/M, where m/M is the ratio of electron to molecule mass. Thus the inverse of this fraction multiplied by the collision frequency can be considered as a characteristic (e^{-1}) time of the elastic energy loss process. At thermal energies the zero field approximation of Phelps, Fundingsland and Brown (1951) for collision probability is utilized. The approximation for elastic collision probability for non-maxwellian gases ($P_c \neq E^{-1/2}$) is $P_c = kE^{1/2}$, where k = 70 in our case. After conversion of the elastic collision probability to a collision frequency versus temperature and pressure we find that the characteristic time for energy loss by elastic collisions is given by $\tau = 0.138/pT$, where p is the pressure in Torr and T is the gas temperature in degrees Kelvin. Figure 3 (curves a and b) illustrates the characteristic times for elastic collision energy loss.

The other source of electron energy loss is by excitation of rotational states in the ambient molecular gas. This source was found by Gerjuoy and Stein (1955) to be approximately 100 times more efficient than elastic collisional energy loss. Because the comparison was made to the G factor found in ionospheric cross modulation experiments, $G = 8m/3M$, the factor 100 is only approximately correct. The two electron loss processes are calculated from the coefficients given by Webber (1962) for three-body attachment to oxygen at thermal energies and by Burch and Geballe (1956) for attachment at energies near 3 eV. The latter process is undoubtedly largely a result of two-body dissociative attachment near the estimated peak attachment cross section at about 4 eV. There is some question to the meaning of an attachment peak at such low energies in view of the energy thresholds, calculated by Thorburn (1953) and Hagstrum (1951) of 4.9 and 6.3 eV, respectively. The 3-eV cross section of 2×10^{-19} cm^2 is likely, however, to represent an accurate estimate of the value actually present in the ionosphere at these electron energies. From examination of the Gaussian nature of the electron energy distribution curve, Figure 2, for photodetached electrons, one can calculate the fraction of electrons produced above a certain energy level. For example, about 30 percent of the electrons photodetached have energies above 3 eV, the necessary endothermic energy value listed by Nawrocki and Papa (1961) for dissociative attachment to oxygen. It is very likely, as outlined in the discussion of Nawrocki and Papa, that the variation of supposed three-body attachment coefficients in the energy region about 4 eV is due to the presence of dissociative attachment and also may be due to distortion of the electron energy distribution function at the higher energies due to the large probability of great energy losses through the attachment mechanism. The calculated two-body characteristic time for the altitude range 30 to 100 km, based upon this reaction cross section and the ARDC model atmosphere is presented by curve c in Figure 3.

Three-body attachment of electrons to oxygen is usually believed to be the major electron loss process in the D region. The three body attachment characteristic time for electrons at thermal energies is calculated from the coefficients presented by Webber (1962) and is presented by curve d of Figure 3. Three body attachment at electron energies of 3 eV has not been specifically isolated as such, since data relating to measurement of this reaction does not allow separation of two body from three body processes. The data of Biondi (1961), for example, strongly suggests that the sharp increase in attachment frequency at energies above 1 eV is due to a threshold process wherein the tail of the electron energy distribution is rapidly raised above a critical energy as the average energy is increased slowly above 1 eV. Therefore no specific three body attachment characteristic time is calculated for electrons at 3 eV. Examination of Figure 3 illustrates the importance of the 3-eV source of electrons and the competitive rotational excitation energy loss process to the overall calculation of ionospheric D region electron gas characteristics. Both of these easily overcome the three body attachment and elastic collisional energy loss processes when the electron energy is high. The characteristic time of the dissociative attachment process decreases with energy, however, so that as the electrons lose energy by inelastic collisions, the probability of undergoing two body attachments rapidly decreases. Calculations of average electron energy and other average characteristics must take this factor into account or they can only be considered as a limit on the parameter studied.

CALCULATION OF EQUILIBRIUM TEMPERATURE CHARACTERISTICS FOR D REGION ELECTRONS

An approximate solution of the distribution function and mean energy equations for electrons in a plasma, wherein the electrons suffer few collisions before loss by attachment, was obtained by Chapman and Cowling (1960). The previously discussed relationship between electron energy loss by rotational excitation and by 2-body attachment at a 3-eV mean energy satisfy the following condition: E(mean electron source energy) $3kT(1 + \tau_1/\tau_2)/2$, where $3kT/2$ is the mean energy of the ambient gas and τ_1 and τ_2 are the characteristic times of attachment and energy loss, respectively. The ratio τ_1/τ_2 is between 3 and 4 for the 30 to 100 km ionospheric region. This expression was derived for elastic energy loss; however, the details of elastic loss versus rotational excitation loss are assumed to be roughly similar because of the high density of available rotational energy states below 3 eV. Under this assumption one may calculate the ratio of the mean equilibrium electron energy, E_{eq} to initial energy E_o = 2.9 eV from the expression $E_{eq} = E_o (1 + \tau_1/\tau_2)^{-1}$ (Chapman and Cowling, 1960) as a function of altitude. Curve a of Figure 4 summarizes these calculations.

An important feature of this approach which indicates a decrease of the actual mean electron energy is the assumption of constant attachment cross section as the electrons decrease in energy through rotational excitation collisions. The cross section varies exponentially below the threshold energy; thus electrons which lose even e^{-1} of their initial energy before attaching, will probably be lost to the attachment mechanism. The exponential cross section behavior makes solution of a Boltzmann equation for the electron energy distribution function quite difficult unless further approximate conditions are specified. If one assumes that only an arbitrary fraction of the initial electron distribution experiences the competitive attachment-rotational excitation processes, one can calculate the equilibrium energies. Figure 4 presents the results for the following choices of this fraction: 100, 30, 10, and 3 percent. The left branch of curve a in Figure 4 represents the decrease in mean electron energy due to the decreasing fraction of photodetached electrons below 50 km. It is interesting to note that even for a very small fraction of electrons undergoing both energy loss and attachment, significantly larger temperatures than the ambient are predicted. Rumi's (1962) datum of 1200 degree electron temperature at 40 km is plotted on Figure 4 as a point at R = 5, H = 40 km. If this measurement is representative of the disturbed ionosphere, then essentially all photo-electrons at this altitude must be experiencing the competitive attachment and energy loss reactions. That is, the energy ratio, for energetic electrons must be about 20:1, if it is assumed that 20 percent of the electrons produced are energetic, and if the electrons are produced at an average energy of 2.9 eV, and the reaction characteristic time ratio is about 3.7. This approach may furnish a new method of obtaining D and E region reaction or energy loss rates if the mean electron energy and one characteristic time can be found independently.

EFFECTS OF ENERGETIC ELECTRON SOURCES ON THE CHEMISTRY OF THE D REGION

The existence of a source of energetic electrons introduces possible complications into the reaction chemistry of the D region of the ionosphere. Reaction of the photo-detached electrons to produce unusual species before their eventual decay to thermal energies is possible, an obvious process being dissociative attachment of electronegative species. Oxygen is the most prevalent of the species and can be considered the only significant contributor. Examination of lists of possible endothermic reactions (see Haaland 1960 or Nawrocki and Papa 1961, for example) show that only a limited number of reactions are likely and these involve species which are much scarcer than molecular oxygen. These are listed in Table II and do not suggest any major modification of D region aeronomy theory, except perhaps the dissociative attachment of water to form the negative hydroxyl ion as an inclusion of additional source of OH in the ionosphere. The contribution of oxygen formed by dissociative attachment of the oxygen molecule is also small in the D to E transition region where downward diffusion of oxygen from the production peak near 110 km is important. In the middle and lower D region three body recombination of atomic oxygen at a rate of approximately $5 \times 10^{-34} T^{1/2} cm^{-6} sec^{-1}$ would produce an equilibrium atomic oxygen density from the dissociative attachment source of the order of 10^7 cm^{-3}, which is much lower than that measured. Thus, this source of atomic oxygen is negligible compared with others and apparently produces no measurable effect upon D region composition.

ACKNOWLEDGEMENTS

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TABLE I

RELATIVE STRENGTH OF ELECTRON SOURCES IN THE LOWER IONOSPHERE

Column	A	B	C	D	E	F	G	H
h-km	α effective (1)	N_eN_+ (2)	N_eN_+ Lyman	q(photo ionization)	q(photo detachment)	q(collisional detachment)	$\frac{E}{D+E+F}$	$\frac{D}{D+E+F}$
30	3.8×10^{-7}				0.35	6.0	0.055	
40	3.8×10^{-7}				0.42	1.8	0.18	
50	3.8×10^{-7}				0.44	0.6	0.423	
60	3.3×10^{-7}	6.8×10^{4}	3.6×10^{4}	2.06×10^{-3}	0.44	0.14	0.76	0.001
70	2.8×10^{-7}	1.54×10^{5}	7.9×10^{4}	5.5×10^{-3}	0.44	3.8×10^{-2}	0.92	0.0125
80	1.8×10^{-7}	1.8×10^{6}	1.8×10^{6}	1.0×10^{-1}	0.48	8.0×10^{-3}	0.83	0.17
90	1.8×10^{-7}			0(1)	0.6	9.0×10^{-4}	0.37 (0)	0.625
100	1.8×10^{-7}			0(10)	0.8	1.2×10^{-4}	0.08 (0)	0.93

1. Webber (1962).

2. Nicolet and Aiken (1960).

TABLE II

IONOSPHERIC REACTIONS INVOLVING ELECTRON ENERGY THRESHOLDS LESS THAN 4 ev

Reaction	Energy Required
$O_2 + e \longrightarrow O^- + O$	3.7 ev
$NO_2 + e \longrightarrow NO + O^-$	1.8
$NO_2 + e \longrightarrow N + O_2^-$	3.6
$N_2O + e \longrightarrow N_2 + O^-$	0.3
$O_3 + e \longrightarrow O_2 + O^-$	0.3
$O_3 + e \longrightarrow O_2^- + O$	0.2
$H_2O + e \longrightarrow H + OH^-$	4.0
$NO_2 + e \longrightarrow NO_2^-$	0.2

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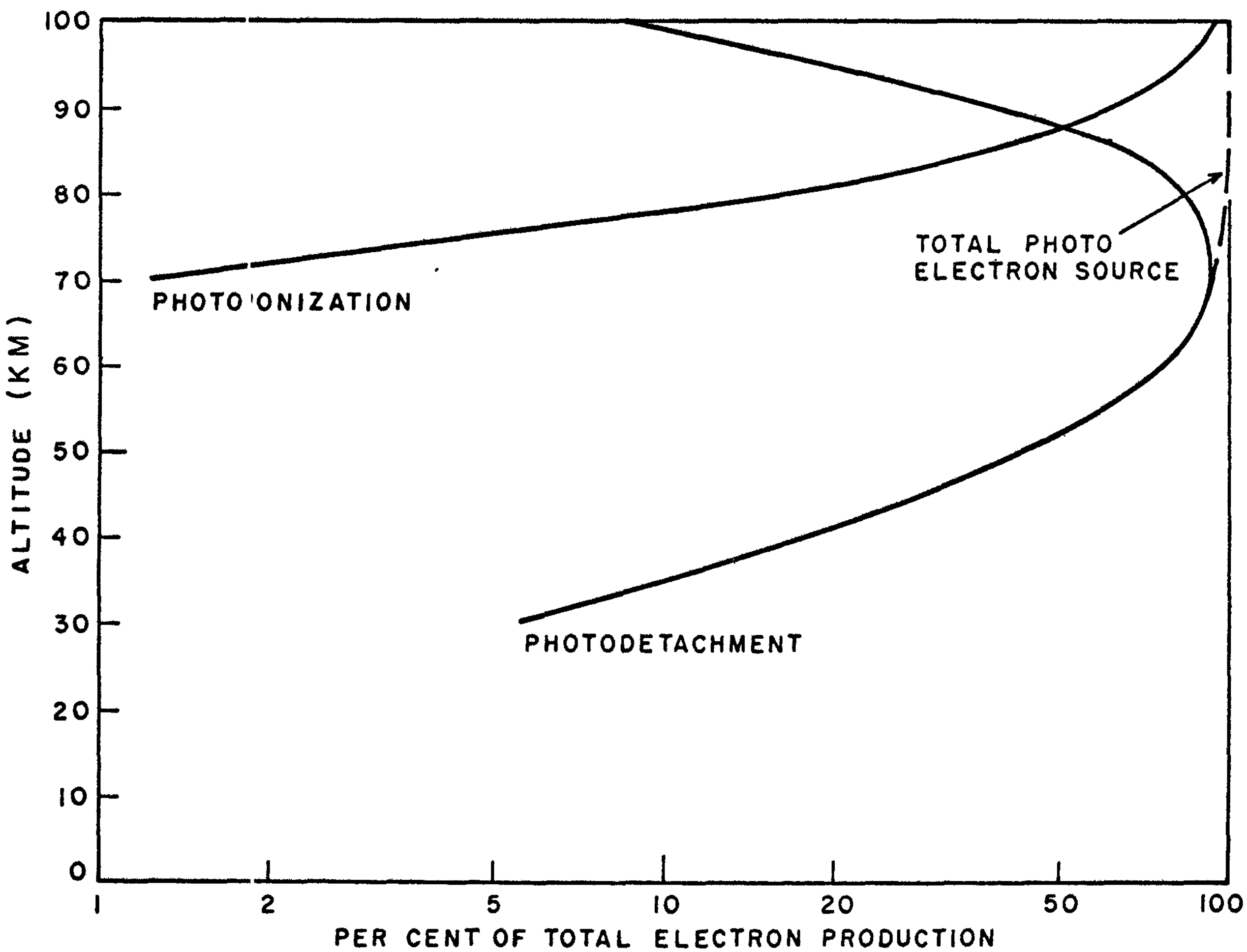

Figure 1

THE FRACTION OF TOTAL FAST ELECTRON PRODUCTION
DUE TO PHOTO PROCESSES IN THE LOWER IONOSPHERE

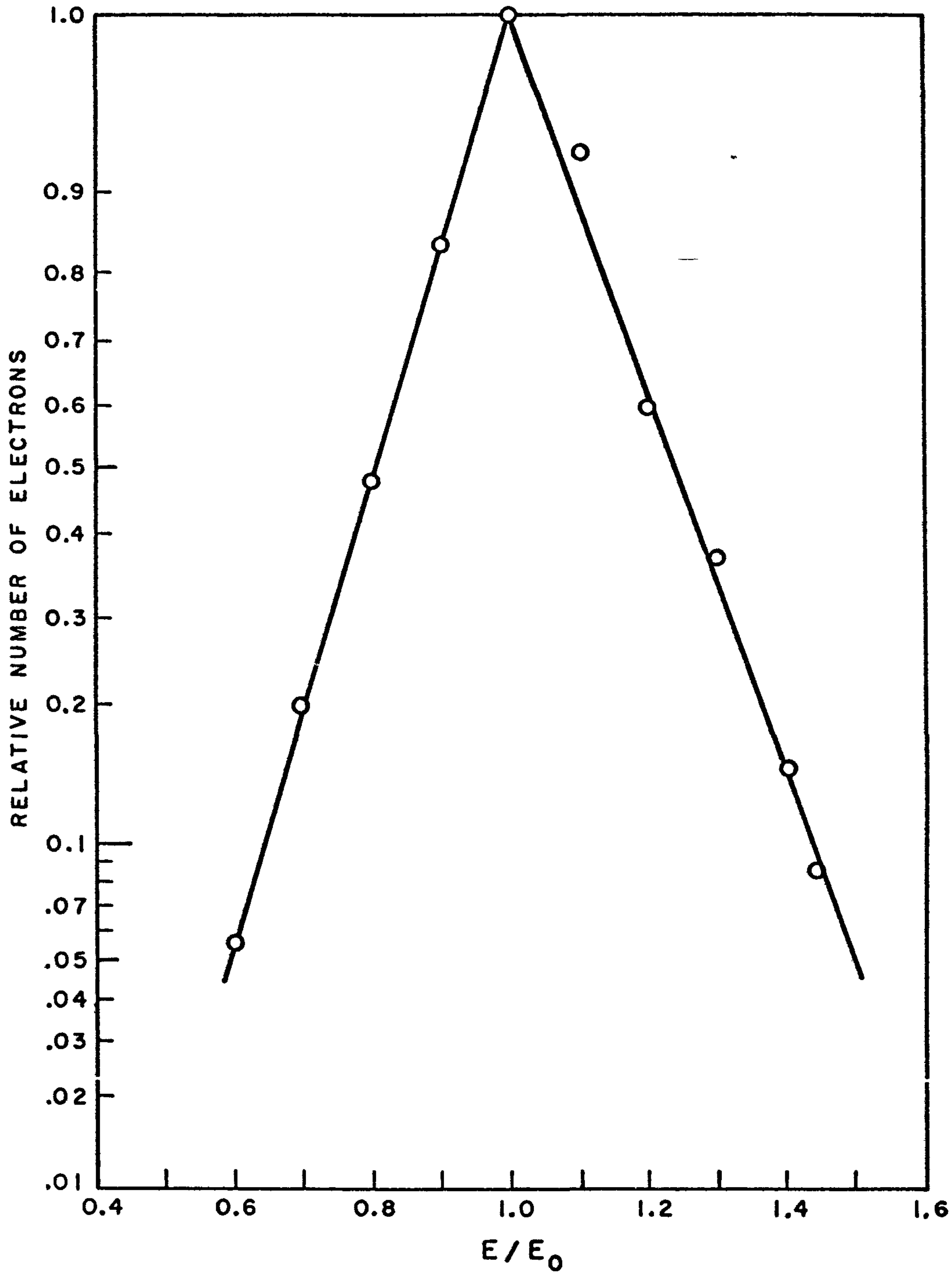

Figure 2

ENERGY DISTRIBUTION OF PHOTODETACHED ELECTRONS ABOUT $E_o = 2.9$ ev

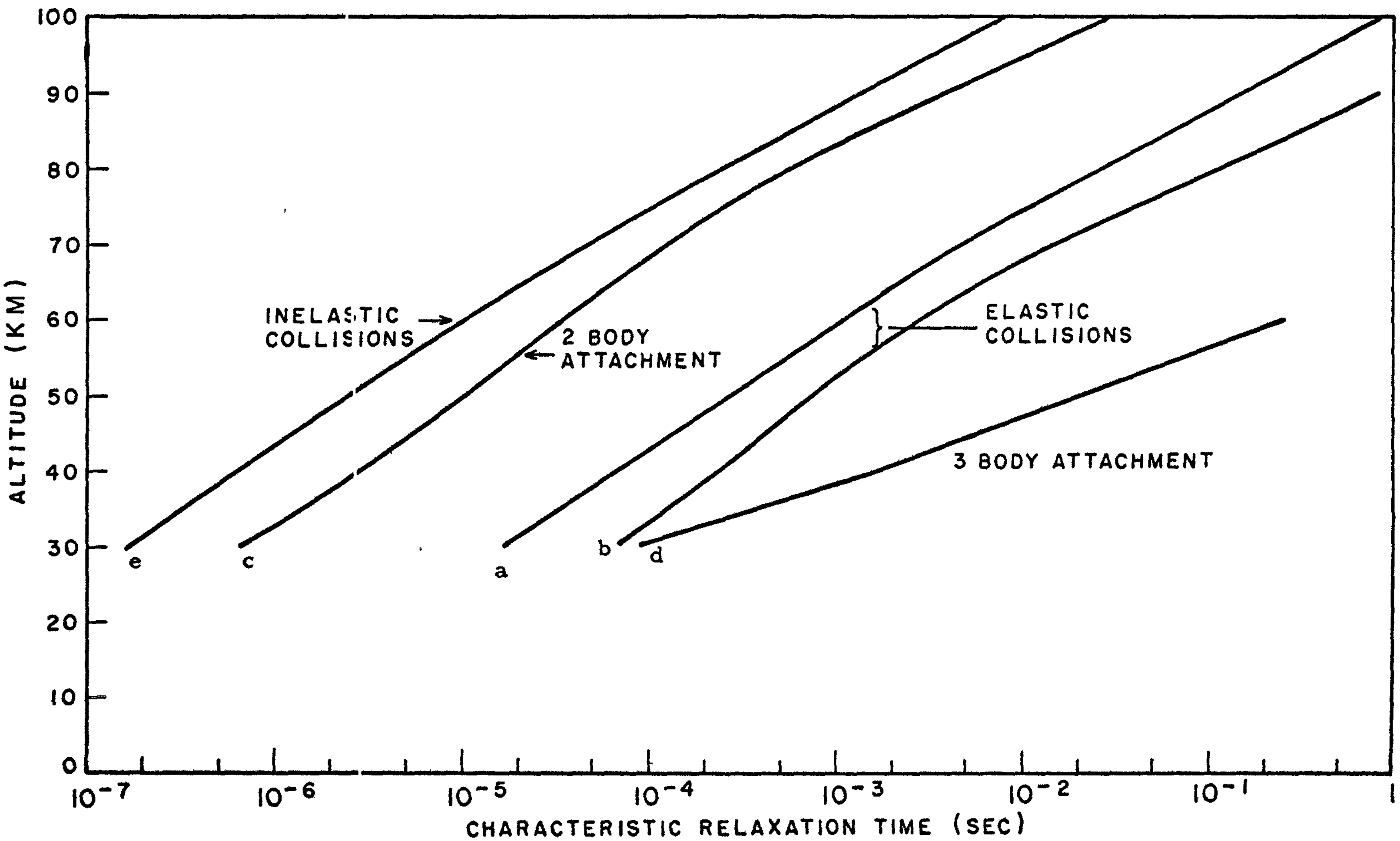

Figure 3

CHARACTERISTIC TIMES OF COMPETING PROCESSES
IN THE LOWER IONOSPHERE

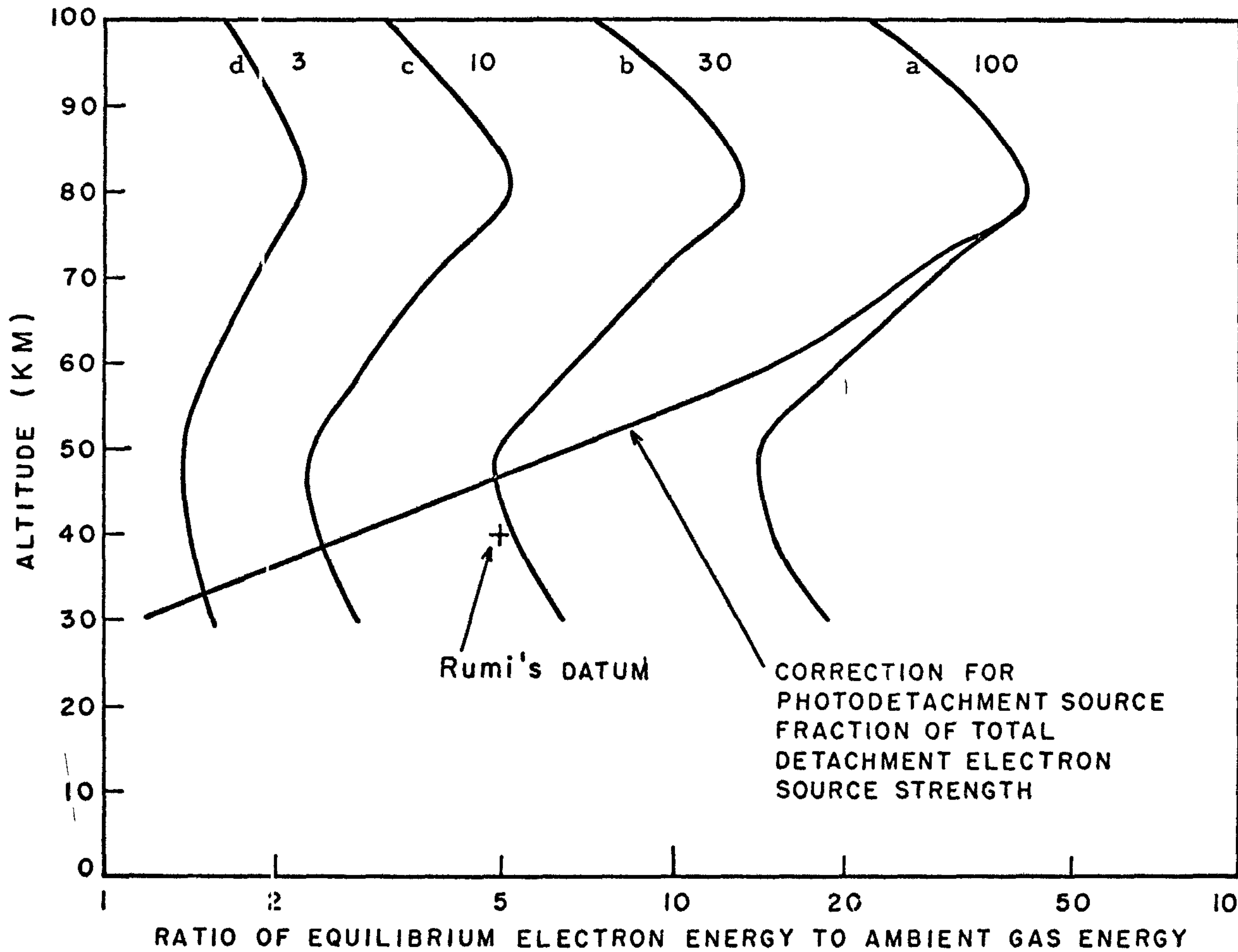

Figure 4

RATIO OF MEAN UPPER LIMIT OF ELECTRON ENERGY TO AMBIENT ENERGY IN THE LOWER IONOSPHERE FOR FRACTIONAL ENERGY LOSS-ATTACHMENT COMPETITION OF 100, 30, 10 AND 3 PERCENT OF TOTAL PHOTODETACHED ELECTRONS

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Electron equilibrium energy in the D and lower E region of the ionosphere is calculated from a relationship between electron energy loss and attachment characteristic times. It is shown that solar photodetachment of electrons from O_2^- ions, which is the major short term ionization source between 50 and 90 km, is a source of energetic electrons of 2.9 ev mean energy. Thus competition between energy loss by rotational excitation of molecules and dissociative attachment to oxygen will exist as the most probable processes for 3 ev electrons. Approximate conditions are defined

1. Upper Atmosphere
2. Electron removal
3. Nonequilibrium electron temperatures

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1. Upper Atmosphere
2. Electron removal
3. Nonequilibrium electron temperatures

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