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SOME RESULTS OF ROCKET EXPERIMENTS IN THE QUIET D REGION

by

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ABSTRACT

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Two electron density profiles have been obtained for the quiet day mid-latitude D region by means of ground to rocket radio propagation experiments. These profiles are interpreted between 85 and 70 km in terms of solar Lyman alpha ionization of nitric oxide. The role of 2 to 10 Ångstrom X-rays is shown to be unimportant to the formation of the D region for the quiet solar conditions present during the two rocket flights. The electron collision frequency in the D region is shown to be subject to significant variations which are correlated to pressure variations of the stratosphere.

Author

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INTRODUCTION

A theory of the formation of the D region was proposed by Nicolet and Aikin in 1960. The sources of D region ionizations under conditions of a quiet sun were explained by solar Lyman alpha ionizing nitric oxide in the altitude region between 85 and 70 km, while ionization below 70 km was attributed to cosmic rays. In the present paper, the results of two rocket experiments are presented together with an interpretation of these results which is consistent with that theory.

Measurements of the atmospheric attenuation of Lyman alpha flux as a function of altitude are used to determine the electron collision frequency profile for each flight. It is shown that the collision frequency is subject to significant variations which are correlated with meteorological processes occurring at the 30 km level of the stratosphere. With a knowledge of the collision frequency, electron density profiles are deduced from the results of radio propagation experiments. Based on satellite data the contribution of 2 to 8 Ångstrom solar X-rays to the ionization of the D region is estimated. Finally a discussion of the different nitric oxide data available since 1960 is given in terms of the effect on the D region recombination coefficient.

The experimental method is based upon the Nike-Apache sounding rocket. The results from two such rocket flights at Wallops Island, Virginia, latitude 38°, are reported here. The first, labeled 14.107, was fired at 1430 hours EST on March 8, 1963, and the second, 14.108, was fired at 1530 hours EST on April 9, 1963. The solar zenith angles were 53° and 55° respectively.

LYMAN ALPHA FLUX

On both flights Lyman alpha flux was measured by means of a lithium fluoride window ionization chamber filled with carbon disulfide gas. For Q_∞, the Lyman alpha flux incident upon the earth's atmosphere, a value of (3 ± 1) x 10^{11} photons cm^{-2} sec^{-1} was obtained. This value is consistent with the results of Friedman et al., (1963) who have shown that the Lyman alpha flux is not strongly dependent upon solar activity.

PRESSURE AND ELECTRON COLLISION FREQUENCY DETERMINATION

The Lyman alpha flux Q(z) that penetrates the atmosphere to an altitude z is given by

$$Q(z) = Q(\infty)e^{-\sigma \int_z^\infty N(z)dz} \qquad (1)$$

where, assuming 0_2 to be the dominant source of absorption, σ is the absorption cross section of an 0_2 molecule and N(z) is the 0_2 number density. Since the partial pressure of 0_2 at an altitude z is defined as

$$P_{0_2}(z) = \int_z^\infty N(z)\ M\ g\ dz \qquad (2)$$

equation (1) can be rewritten as

$$Q(z) = Q(\infty)e^{-\frac{\sigma P_{0_2}(z)}{M\ g}} \qquad (3)$$

where M is the mass of an O_2 molecule and g is the gravitational acceleration. A measurement of the ratio $Q(\infty)/Q(z)$ yields therefore the partial pressure of O_2 from which, assuming a constant ratio between oxygen and nitrogen partial pressures, the total pressure is derived.

The derived pressures can be used to obtain the collision frequency of electrons with neutral molecules. Phelps (1960) from laboratory measurements has shown that ν, the electron collision frequency in air for monoenergetic electrons, is proportional to the electron energy. From this and the gas law it follows that for monoenergetic electrons of energy kT, the collision frequency is proportional to the atmospheric pressure. The relationship is

$$[\nu]_{AIR} = 9 \times 10^{7}\ p\ (\mathrm{mmHg})\ \sec^{-1} \qquad (4)$$

The results of the pressure determinations on flights 14.107 and 14.108 are shown on Figure 1. The resolution in the pressure measurements, indicated by the horizontal bars, is determined by the precision to which the Lyman alpha ion chamber aspect angle is known. Included in this figure is the pressure profile determined by Smith et al., (1964) who performed a rocket-borne grenade experiment at Wallops Island five hours after flight 14.107. It is believed that the indicated pressure differences in these three measurements are real and indicate the presence of meteorological effects in the mesosphere.

METEOROLOGY

From Equation (4) of the previous section it can be expected that the D region collision frequency profile will be subject to the diurnal, seasonal and latitudinal variation of mesospheric pressure that the work of Stroud and Nordberg (1961) and others has revealed.

In Figure 2 is shown for Wallops Island a plot of the altitude of the 10 millibar pressure level for a three year period. In addition to the very apparent seasonal variation comparable short term variations are present, particularly during winter. The Meteorologische Abhandlunge Vol. XL, 1963, from which these data are taken shows that a sudden warming event occurred in the stratosphere over Canada on April 4. By April 9 the effects of this event could be noticed at Wallops Island where the altitude of the 10 millibar level increased from 30.80 km on March 8 to 31.16 km on April 9 while the temperature of this level increased from -47°C to -36°C. These stratospheric changes lend support to our April 9 collision frequency profile since the mesosphere is linked to the stratosphere through the pressure relation

$$p(z) = p_o e^{-\int_{z_o}^{z} dz/H(z)} \qquad (5)$$

where the scale height H(z) is proportional to the temperature T(z). Although no measurements of T(z) exist for 14.108 a reasonable model can be constructed which leads to mesospheric pressures of the required magnitude.

Convincing evidence for the existence of an ionosphere-stratosphere interaction has been given by Bossolosco and Elena (1963) who have shown that a strong correlation exists between the temperature at the 10 millibar level and mid-latitude winter radio wave absorption at frequencies around 2 Mc/s. Their results show a temperature increase of 20° at the 10 millibar level correlated with a factor 2 increase in absorption. Our results would seem to indicate that this effect, the so called winter absorption anomaly, is due simply to an increase in mesospheric pressure. However, since radio wave absorption involves the electron density as well as collision frequency, and since both the electron production and loss mechanisms are pressure dependent, such a conclusion must be withheld until quantitative calculations have been made.

ELECTRON DENSITY PROFILES

The electron density profiles reported here were obtained by means of radio propagation techniques employing ground to rocket transmissions. In flight 14.107 linearly polarized signals were transmitted from the ground at frequencies of 3.0 and 4.9 Mc/s. The mechanical spin of the rocket of about 3 cycles per second was used to rotate the rocket-borne receiving antennas through the polarization patterns of the arriving waves. The telemetered signal strengths exhibited a fading pattern, the frequency of which was the sum of the rocket spin frequency and the ionospheric Faraday rotation frequency. A comparison of the period of this fading pattern with the mechanical spin period, independently measured by means of a solar aspect sensor, yielded the Faraday rotation of the plane of polarization.

Under the condition of quasi-longitudinal propagation, the plane of linear polarization, defined by the angle ψ, rotates with rocket altitude z according to an expression of the form

$$\frac{d\psi}{dz} = N_e(z)\ F(\omega,\ \omega_H,\ \nu(z)) \qquad (6)$$

where $N_e(z)$ is the electron density and F is a function of the exploring frequency ω, the gyrofrequency ω_H and the collision frequency ν. The explicit form of F involves the Dingle integrals of the generalized Appleton-Hartree formula (Sen and Wyler, 1960). Before F(z) can be evaluated it is necessary to have a collision frequency model, the determination of which was described in section 2. The Faraday rotation experiment by itself allows the collision frequency to be determined at a single altitude. This follows from the fact that the function $F(\omega, \omega_H, \nu(z))$ changes sign at a unique value of ν/ω. By noting the altitude at which the reversal in the sense of the Faraday rotation occurred on flight 14.107 a value of $\nu = 13.8 \times 10^6$ sec^{-1} was deduced for an altitude of 61 ± 2 km. As seen in Figure 1 this value is consistent with the March 8 pressure profile obtained from the grenade experiment of Smith et al., (1964).

The electron density results of the 14.107 Faraday rotation experiment at 3.0 Mc/s are shown in Figure 3. Each point is the average electron density in an altitude interval of approximately one kilometer. The horizontal bar indicates the probable uncertainty in the determination of this average value. This uncertainty is due to random echoes from above the D region distorting the Faraday pattern. This effect was more severe on the 4.9 Mc/s Faraday experiment which yielded electron densities in agreement with those shown in Figure 3, but with uncertainties two to three times as large.

In flight 14.108 linearly polarized signals were transmitted at frequencies of 1.8 and 4.9 Mc/s. A 3.0 Mc/s signal was also transmitted from ground to rocket on flight 14.108, but in this case the transmitted pattern was alternately switched between opposite circularly polarized modes, which in the ionosphere were differentially absorbed. Denoting the received signal strength of the two polarization modes as E_o and E_X, the altitude variation of the logarithmic ratio $\ln(E_o/E_X)$ can be expressed as

$$\frac{d}{dz} \ln(E_o/E_X) = N_e(z)\ G(\omega,\ \omega_H,\ \nu(z)) \qquad (7)$$

where again $N_e(z)$ is the electron density and $G(z)$ is an altitude dependent function involving the Dingle integrals and requiring a collision frequency model for explicit evaluation.

In addition to a direct comparison of circularly polarized E_o and E_X signal strengths, it is possible to obtain differential absorption data also from the Faraday pattern of a linearly polarized signal. This follows from the fact that the maximums in the Faraday pattern represent the sum, while the nulls represent the difference of the E_0 and E_X signal strengths. This technique was the basis of the 1.8 Mc/s experiment.

The results of the three propagation experiments on flight 14.108 are shown in Figure 4. The electron densities deduced from the 4.9 and 1.8 Mc/s propagation experiments are relatively insensitive to the choice of collision frequency profile. This is not true however for the 3.0 Mc/s differential absorption experiment. In Figure 4 are shown two electron density profiles deduced from the 3.0 Mc/s differential absorption measurement, the open circle points were computed using the Figure 1 pressure values of Smith, while the values shown as crosses were computed using a 50 percent higher pressure profile. It is seen that consistency between the results of the 14.108 Faraday experiment on 4.9 Mc/s and the 14.108 differential absorption experiment on 3.0 Mc/s requires collision frequency values which between 75 and 80 km are approximately 50 percent higher than those observed one month previously. This requirement is satisfied by the Lyman alpha data shown in Figure 1. For comparison with the 14.107 electron densities the results from 14.108 are plotted as the dashed line in the previous Figure 3. The similarity of the two profiles is apparent, particularly with respect to the minimum at the mesopause (83 km). Possible causes of the minimum at the mesopause include a temperature dependent nitric oxide distribution, and the attachment of electrons to dust. This latter hypothesis has some support from the work of Witt et al., (1962) who reported the detection of dust in the vicinity of the mesopause, and the work of Frocco and Smullin (1963) who reported scattering of a laser beam in this altitude region.

In order to interpret the electron density profiles presented here it is necessary to have a knowledge of the ion pair production function for each of the ionizing radiations affecting the D region. This is the subject of the following sections.

COSMIC RAY IONIZATION

The contribution of cosmic rays to the ionization content of the normal D region has been considered by Nicolet and Aikin (1960). They showed an ion production rate which was important below 70 km and which involved a variation of a factor 10 between the geomagnetic latitudes of 0^{o} and 70^{o}. For a geomagnetic latitude of 50^{o}, based on the work of Webber (1962), a slightly revised ionization rate of 180 $\pm$ 30 ion pairs/sec/atmosphere can be assumed for the altitude region between 60 and 85 km for the

1963 portion of the solar cycle. Combining this value with a model atmosphere yields the altitude dependence of the cosmic ray ionization rates shown as the lower portion of the curves labelled q_{O_2} and q_{N_2} in Figure 5.

X-RAY IONIZATION

The major atmospheric constituents of the D region can be ionized by solar X-rays in the 2 to 8Å wavelength region. The importance of this process will depend, however, upon the degree of solar activity. Instrumentation failure prevented a direct measurement of 2-8Å X-rays during our flights. Thus it is necessary to rely on estimates of the flux. The basis of these estimates are the 2800 Mc flux as measured at Ottawa, the McMath-Hulbert calcium plage data, and the Zurich provisional sunspot number. White (1964) has compared direct measurements of X-ray flux from the OSO-1 satellite with these indices and derived an empirical relation for estimating the X-ray intensity. From these data White estimates that the 2 to 8Å flux was the same to within 50 percent during both our rocket flights and had an integral value of 1.9×10^{-4} ergs/cm^{2}sec.

From Ariel I satellite, Pounds et al., (1961) have obtained solar spectra between 6 and 11Å. The crosses in Figure 6 show a typical non-flare spectrum in which the integrated intensity below 8Å was 1.3×10^{-4} ergs/cm^2/sec. According to White (1963) both the Ariel I and OSO-1 non-flare data can be fitted to a frequency spectrum of the form $J(\nu)d\nu \propto e^{-h\nu/kT}d\nu$ with T equal to 2.8×10^6 °K. This is shown as the solid curve of Figure 6.

Using the ionization cross sections given by Nicolet and Aikin (1960) together with a model atmosphere derived from the Smith pressure profile and the spectral distribution of Figure 6 (normalized to an integral value of 1.9×10^{-4} ergs/cm^2/sec), the ion pair production function due to X-rays can be calculated as a function of altitude. The results are shown as the upper portion of the curves labelled q_{O_2} and q_{N_2} in Figure 5. Before the relative importance of ion pair production by X-rays can be evaluated, it is necessary to have some knowledge of the concentration of nitric oxide, which is the trace constituent ionized by the Lyman alpha flux.

NITRIC OXIDE

For sufficiently large concentrations of atomic nitrogen estimates of the nitric oxide distribution can be based upon the processes

$$N + O_2 \rightarrow NO + O \tag{8}$$

and

$$N + NO \rightarrow N_2 + O \tag{9}$$

which have rate coefficients b_1 and b_2 respectively. The density of NO in the D region is then determined by

$$n(NO) = (b_1/b_2)\, n(O_2) \tag{10}$$

Nicolet and Aikin (1960) adopted $5\text{x}10^{-10}$ as the ratio b_1/b_2. The ion-pair production function resulting from such a distribution is shown as curve 1 of Figure 5. A laboratory measurement of b_1/b_2 by Clyne and Thrush (1961) yielded a value of $9\text{x}10^{-9}$. The ion-pair production function for this nitric oxide distribution is labeled curve 2 in Figure 5. Barth (1964) has made a direct measurement of the nitric oxide concentration in the upper atmosphere and has obtained a value of $6.2\times10^{7}cm^{-3}$ between 75 and 85 km. If this density is used in Equation (10) for an altitude of 80 km, then a b_1/b_2 ratio of 9×10^{-7} is obtained. The resulting production function is shown as curve 3 in Figure 5. Table I summarizes the nitric oxide information for an altitude of 80 km. Also tabulated for this altitude are three derived values of the recombination coefficient α. This parameter is the topic of the following section.

TABLE I

Curve #	b_1/b_2	n(NO (cm^{-3})	α(cm^3/sec)
1	5×10^{-10}	4×10^{4}	2×10^{-8}
2	9×10^{-9}	6×10^{5}	3×10^{-7}
3	9×10^{-7}	6×10^{7}	3×10^{-5}

RECOMBINATION COEFFICIENT

The electron densities of Figure 3 are related to the ion production functions of Figure 5 by the equation

$$N_e^2 = \Sigma_i q_i/\alpha_i \qquad (11)$$

where α_i is the effective recombination coefficient of the i^{th} species of positive ion. Biondi (1964) has indicated that O_2^+ and N_2^+ recombine dissociatively with a rate coefficient of $2\times10^{-7}cm^{3}sec^{-1}$, while NO^+ has a recombination coefficient of less than $5\times10^{-7}cm^3sec^{-1}$. The values of recombination coefficient derived from curves 1 and 2 of Figure 5 and given in Table I are consistent with dissociative recombination of NO^+ as the electron loss process of the D region. Curve 3 requires the introduction of loss processes not previously considered in D region theory since $10^{-6}cm^3sec^{-1}$ is the upper limit assigned to dissociative recombination by both laboratory measurements and theoretical determinations.

By using in Equation (11) the recombination coefficients given by Biondi together with the ion production functions shown in Figure 5, it is seen that the ionization due to X-rays can dominate the quiet D region only above 83 km and even then only for the case of a nitric oxide distribution corresponding to curve 1 of Figure 5.

CONCLUSION

Electron density and collision frequency profiles have been obtained for the quiet day mid-latitude D region. The electron collision frequency is subject to significant variations of a meteorological nature. The electron density profiles agree with the theory that for a reasonably quiet sun solar X-rays are unimportant, and Lyman alpha ionization of nitric oxide is the major contributor to the ionization content of the D region. Although existing theory can explain these measured profiles, the recent nitric oxide measurements of Barth (1964) would, if accepted, require a reevaluation of the electron-ion loss processes.

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FIGURE CAPTIONS

1. Atmospheric pressure versus altitude at Wallops Island measured at 14:30 hours (14.107) and 19:00 hours (Smith et al.,), March 8, 1963, and at 15:30 hours, April 9, 1963 (14.108).
2. Seasonal variation of the altitude of the 10 millibar pressure level at Wallops Island.
3. Electron density versus altitude for March 8, 1963 (14.107). Dashed curve is a composite of the results shown in Figure 4.
4. Electron density versus altitude for April 9, 1963 (14.108) showing the effect of the choice of collision frequency model used to interpret radio absorption data.
5. Calculated ionization production function versus altitude. Curves labeled 1, 2 and 3 show the effect of Lyman alpha flux on three different nitric oxide distributions.
6. Quiet sun spectrum in the 2 to 10 Ångstrom wavelength interval. Solid curve is the spectral distribution $J(\nu)d\nu = Ae^{-h\nu/kT}d\nu$, with T equal to 2.8×10^6 °K.

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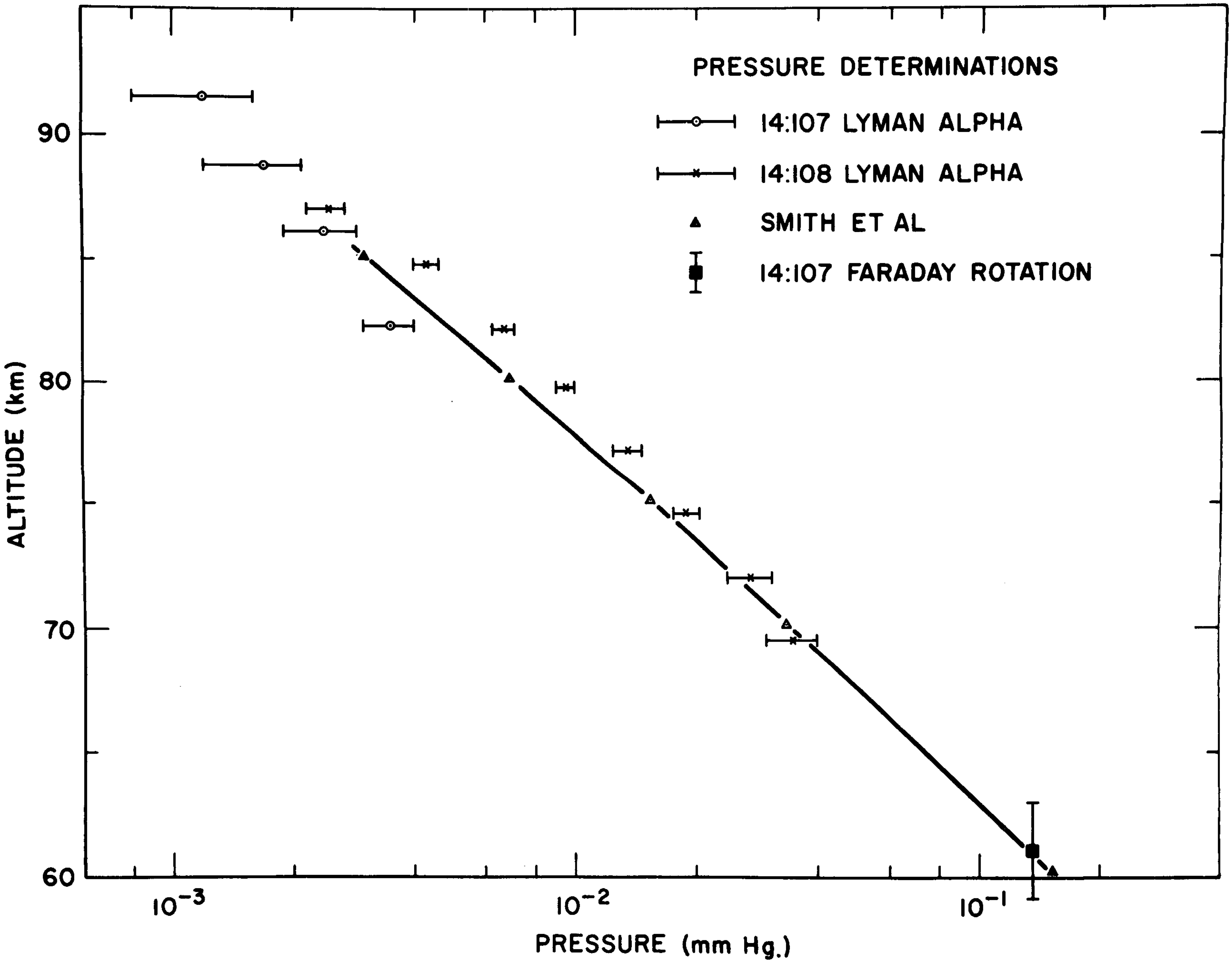
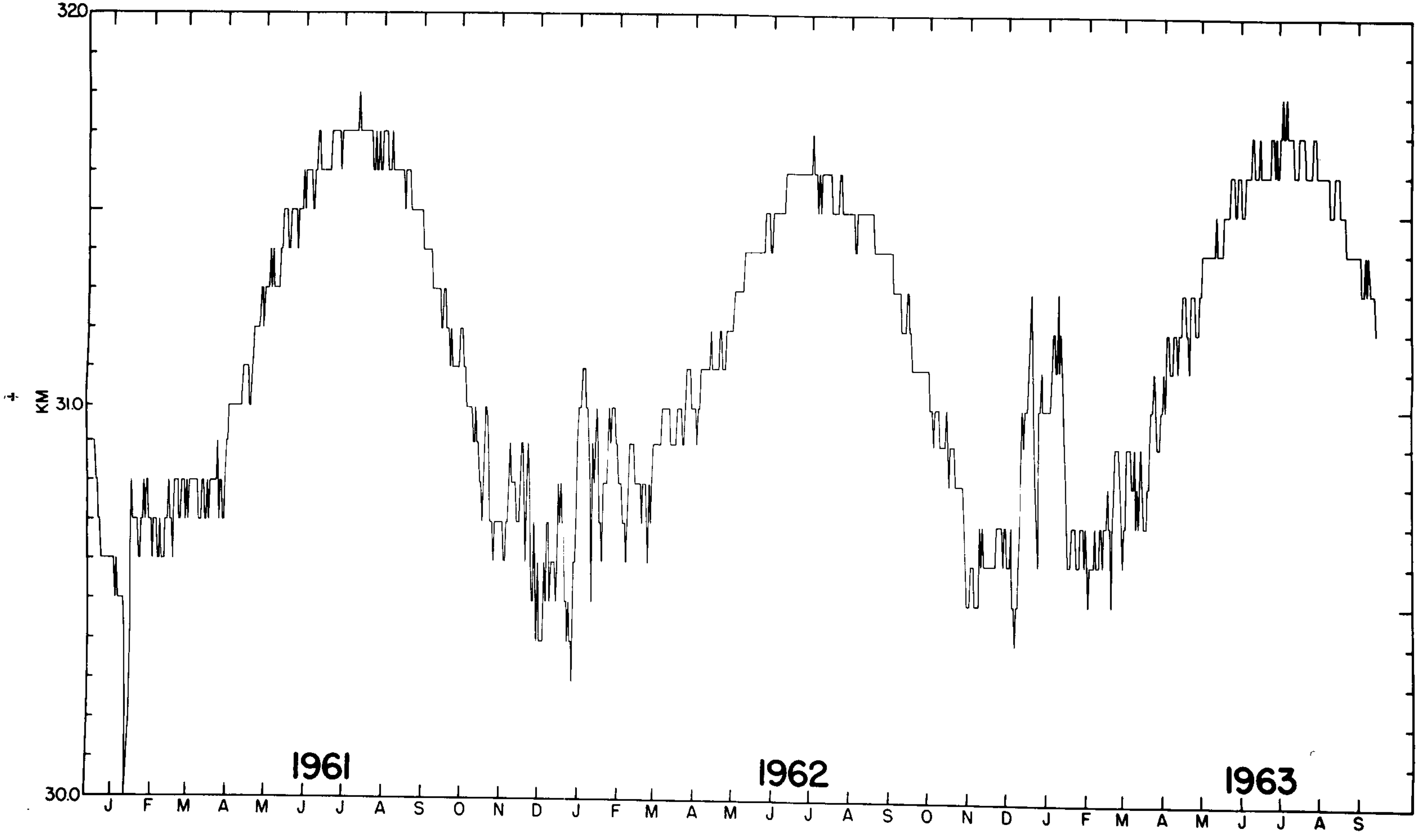

PRESSURE DETERMINATIONS
14:107 LYMAN ALPHA
14:108 LYMAN ALPHA
SMITH ET AL
14:107 FARADAY ROTATION
90
80
70
60
ALTITUDE (km)
10^{-3}
10^{-2}
10^{-1}
PRESSURE (mm Hg.)

FIGURE 1.



32.0
31.0
30.0
KM
J
F
M
A
M
J
J
A
S
O
N
D
J
F
M
A
M
J
J
A
S
O
N
D
J
F
M
A
M
J
J
A
S
1961
1962
1963

FIGURE 2.

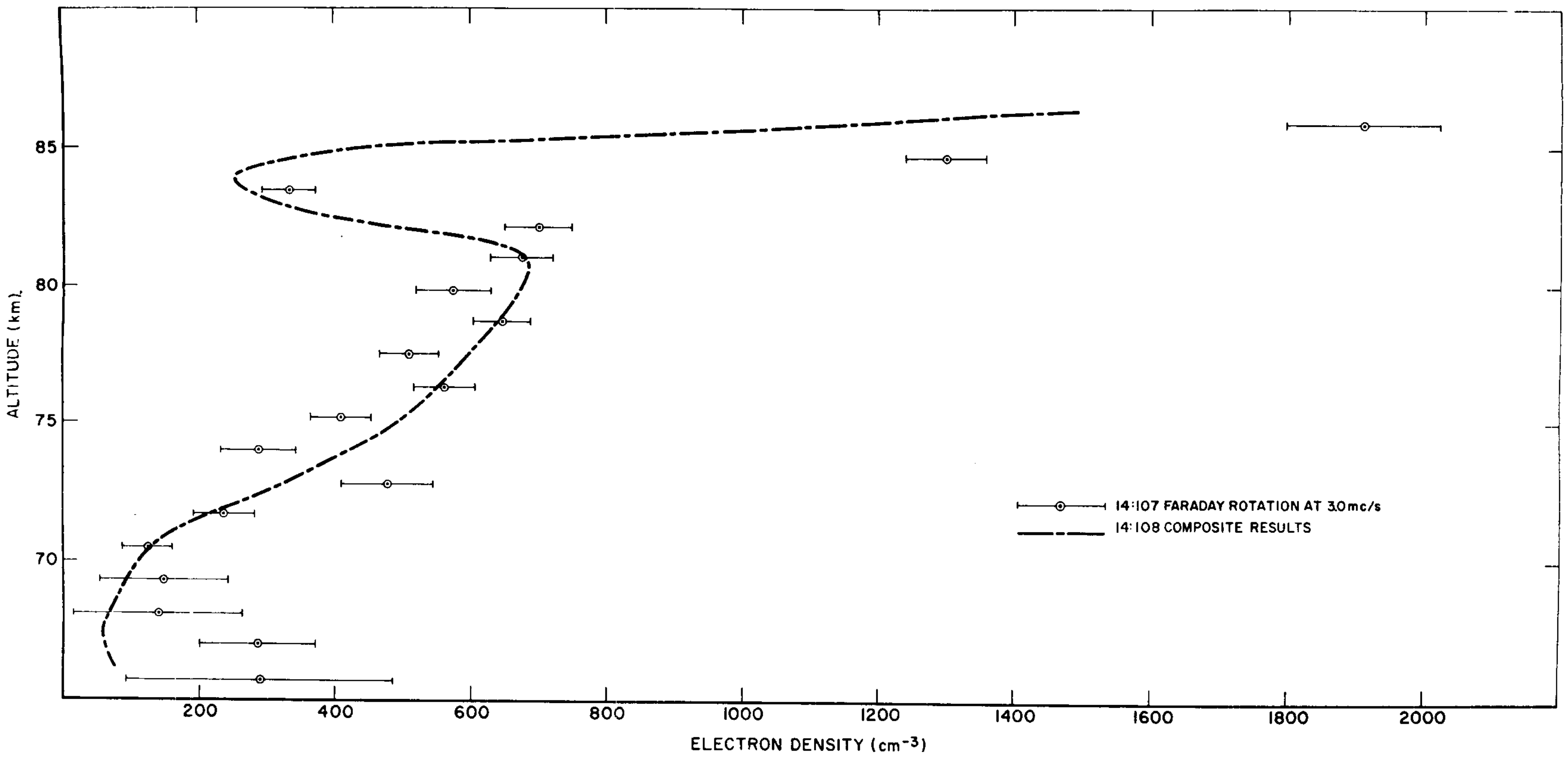

85
80
75
70
ALTITUDE (km)
200
400
600
800
1000
1200
1400
1600
1800
2000
ELECTRON DENSITY (cm⁻³)
14:107 FARADAY ROTATION AT 3.0 mc/s
14:108 COMPOSITE RESULTS

FIGURE 3.

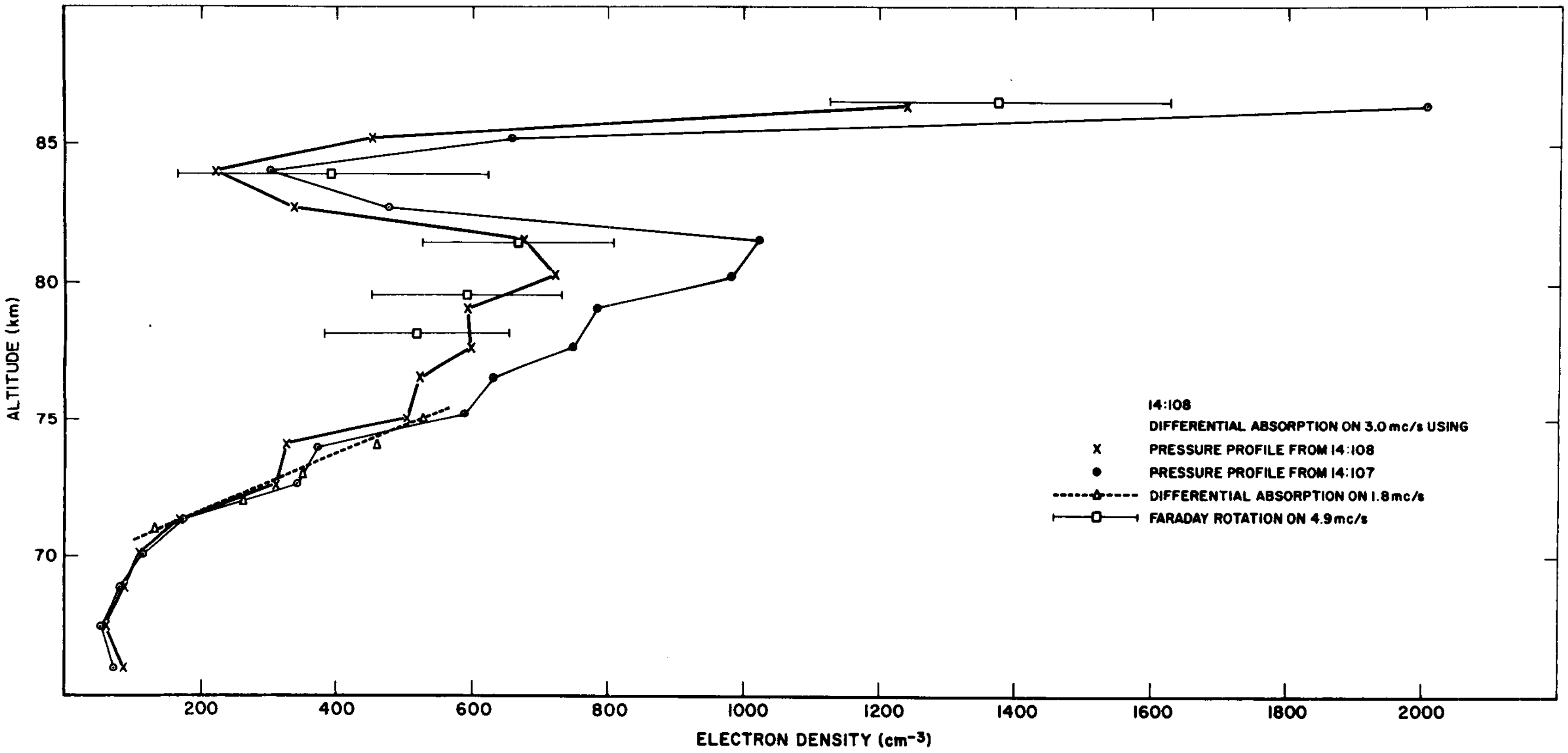

14:108
DIFFERENTIAL ABSORPTION ON 3.0 mc/s USING
× PRESSURE PROFILE FROM 14:108
● PRESSURE PROFILE FROM 14:107
DIFFERENTIAL ABSORPTION ON 1.8 mc/s
FARADAY ROTATION ON 4.9 mc/s
ALTITUDE (km)
85
80
75
70
ELECTRON DENSITY (cm⁻³)
200
400
600
800
1000
1200
1400
1600
1800
2000

FIGURE 4.

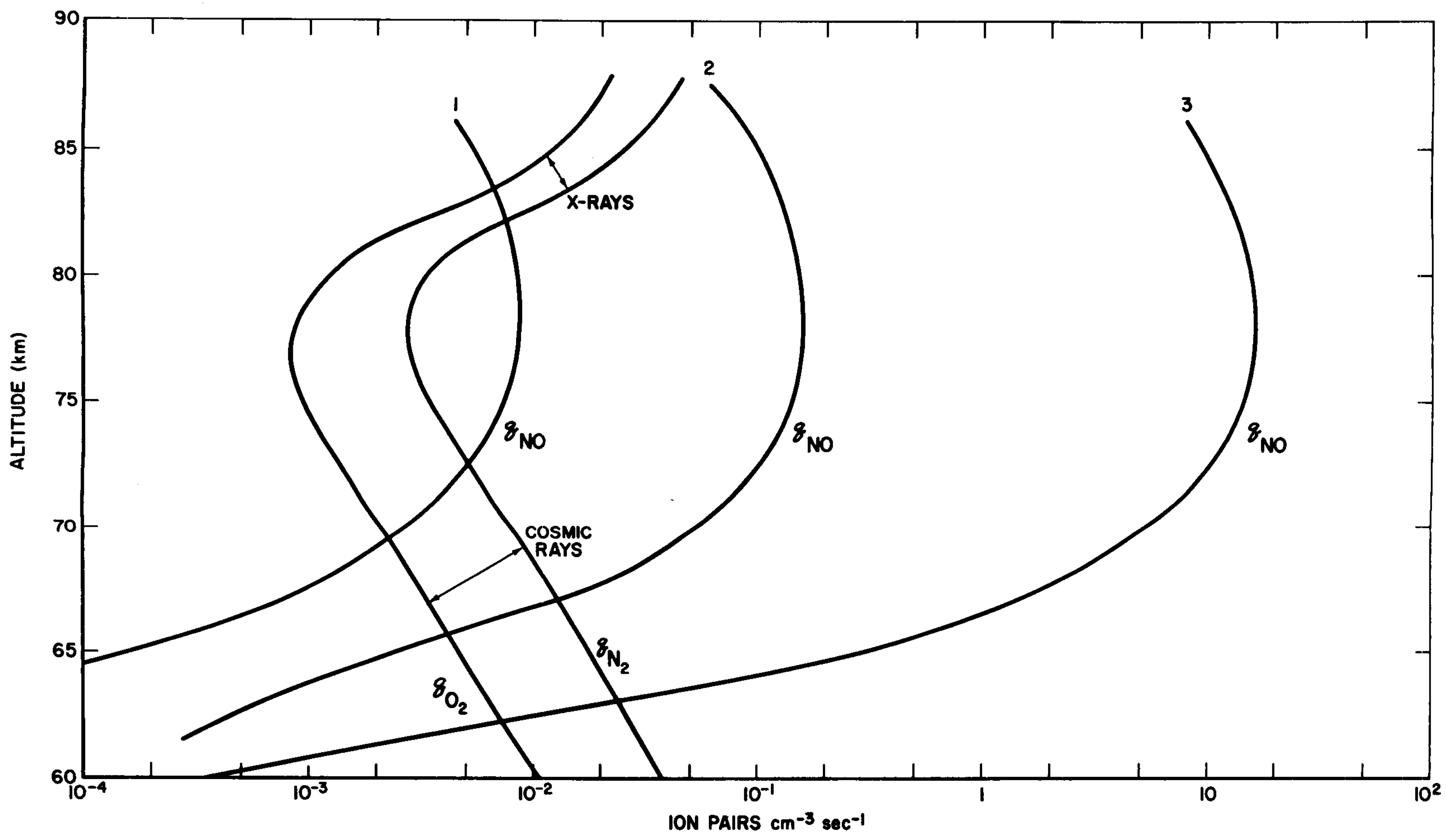

90
85
80
75
70
65
60
ALTITUDE (km)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
ION PAIRS cm^{-3} sec^{-1}
1
2
3
X-RAYS
COSMIC RAYS
q_{NO}
q_{NO}
q_{NO}
q_{N_2}
q_{O_2}

FIGURE 5.

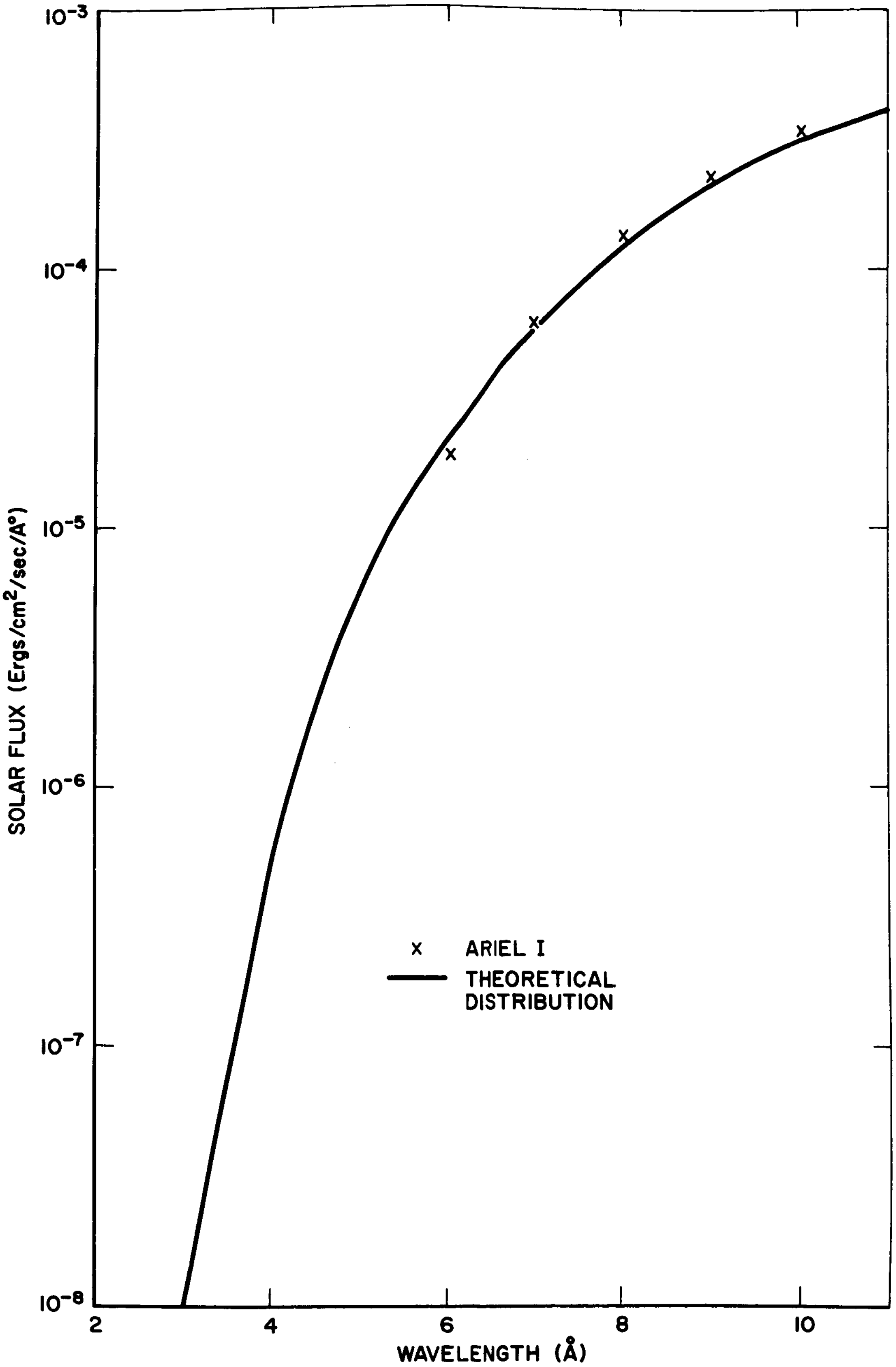

10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
SOLAR FLUX (Ergs/cm²/sec/A°)
2
4
6
8
10
WAVELENGTH (Å)
x ARIEL I
THEORETICAL DISTRIBUTION

FIGURE 6.