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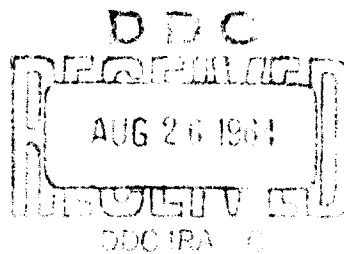
Environmental Research Papers
No. 32



Electrical Processes in the Nighttime Exosphere

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M. SMIDDY



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Electrical Processes in the Nighttime Exosphere

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Electrical Processes in the Nighttime Exosphere

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Abstract. The results of nighttime measurements of positive ion densities between 240 and 1875 km are presented. The ion scale height is found to change abruptly around 600 km, increasing from 120 km at 500 km to 1400 at 640 km; it increases gradually with height above this level. An ion temperature of $1050 \pm 50^\circ\text{K}$ is deduced from the ion scale height measured above the peak of the *F* region. The ion-density measurements were obtained by means of a spherical electrostatic analyzer flown on a Blue Scout rocket. In the altitude region 280 to 350 km the ion-density values agree to within 15 per cent with the electron-density measurements obtained from local ground-based ionosondes. The vertical distributions of the principal light ions above 400 km are calculated, assuming the existence of diffusive equilibrium. The relative abundance of the different ionic species at the reference level is determined from the measured profile of the total ion density. The results of the nighttime flight show that the atomic oxygen ion is the principal constituent below 530 km and ionized hydrogen the major constituent above 550 km. An upper limit is placed on the helium ion distribution, which attains its maximum value at 550 km. At this level it constitutes a maximum of about 7 per cent of the total ion density. The ion-atom interchange coefficient for the production of NO^+ is calculated from the variations with time of charge densities in the altitude region 280 to 300 km; the coefficient is found to vary between 2 and $4 \times 10^{-12} \text{ cm}^2 \text{ sec}^{-1}$.

INTRODUCTION

By the method described in an earlier paper [Sagalyn *et al.*, 1963] positive ion densities have been measured over the altitude region 240 to 1860 km during a nighttime flight of a Blue Scout rocket. A third mode of operation was added to obtain new information about the positive ion energy distribution. The results are compared with day and nighttime electron-density profiles obtained by other techniques. Ion temperature and the average ion mass and scale height are determined as a function of altitude from the experimental results.

Nicolet [1961], Hanson [1962], Bauer [1962], Bourdeau and Bauer [1963], Ulwick and Pfister [1963], Mange [1960, 1961], Donley [1963], and others have presented theoretical discussions or experimental results on charged particle distributions above the ionization maximum in the *F* region. Applying equations derived by Mange [1960], Hanson [1962], and Bauer [1962] we have calculated the altitude distribution of the individual light ion species above the level where diffusive equilibrium may be assumed to exist. The reference-level composition is deduced from the analysis of the vertical distribution of the total ion concentration obtained on the Blue Scout flight. The vertical profiles of

atomic oxygen and hydrogen ions are obtained for altitudes above 400 km; an upper limit is given for the helium-ion distribution. The results are compared with other nighttime measurements.

Langstroth and Hasted [1962], Talrose *et al.* [1962], Galli *et al.* [1963], and Sayers and Smith [1963] have carried out laboratory measurements of the ion-atom interchange rate coefficient for the formation of NO^+ , an important ion loss process in the nighttime *F* region. The applicability of their results to the ionosphere is not certain, as the experiments usually provide only an upper limit for the reaction; also, the reactants in the laboratory and ionosphere may not be in the same states. Yonezawa *et al.* [1959], Bates and Nicolet [1960], Danilov [1960], and others have calculated values for this reaction from upper atmospheric data under various assumptions. The results vary by three orders of magnitude.

The ion-atom interchange coefficient for the formation of NO^+ is calculated in this report using nighttime variations of charged densities obtained from the Blue Scout data and electron-density profiles from a local ionosonde station. The continuity equation is solved under the assumption that between 280 and 300 km the time variation of positive ions is principally due

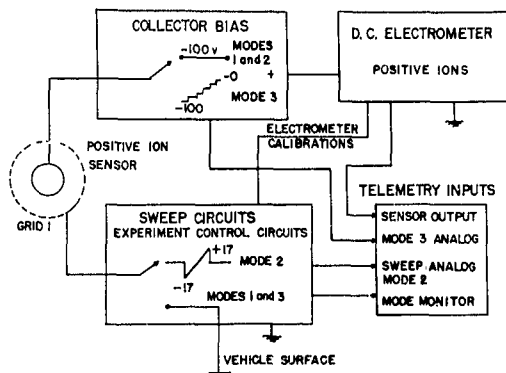


Fig. 1. Simplified block diagram of spherical electrostatic analyzer.

to ion-atom interchange, diffusion, and radiative recombination.

THE EXPERIMENT

A simplified block diagram of the spherical electrostatic analyzer experiment is shown in Figure 1. This experiment is an extension of the spherical ion probe first used by *Gringauz and Zelikman* [1957] and *Gringauz et al.* [1961] for satellite measurements. The experiment is operated in three modes.

Mode 1. A fixed saturation voltage is applied between grid 1 and the collector. As shown in *Sagalyn et al.* [1963] the ion density N is related to the collector current i through the relation

$$i = \frac{\pi}{2} r^2 N e c f(V) \alpha \cdot \left[e^{-x^2} + \pi^{1/2} \left(x + \frac{1}{2x} \right) \operatorname{erf}(x) \right] \quad (1)$$

where

r = radius of grid 1.

e = ion charge.

c = most probable ion velocity.

q = rocket velocity.

α = experimentally determined transmission factor for grid 1.

$x = 2q/c\pi^{1/2}$.

$f(V)$, a function of rocket potential V , is obtained from mode 2 analysis.

$$\operatorname{erf}(x) = \frac{2}{\pi^{1/2}} \int_0^x \exp(-y^2) dy.$$

Mode 2. Saturation voltage is maintained between grid 1 and the collector while a linear sweep voltage, range ± 17 volts, duration 3 seconds, is applied to grid 1. The rocket potential V_R and $f(V)$ of equation 1 are obtained from the resulting current voltage curves. Current voltage curves obtained at 436 and 1650 km on a Blue Scout flight launched on April 12, 1961, are shown in Figure 2. The analysis of this mode is given in *Sagalyn et al.* [1963], where it is shown that

$$V_R = (m/2e)(q + 2.3c)^2 - \Delta V_1 \quad (2)$$

where

V_R is the rocket potential with respect to the undisturbed plasma.

m = mass of heaviest ion in the gas.

c = most probable ion velocity.

ΔV_1 = value of sweep voltage corresponding to complete retardation of most energetic ions in the gas.

Values of $f(V)$ and V_R measured as a function of altitude on the Blue Scout flight are given in Table 1.

The analysis of mode 2 data to obtain ion mass and temperature will be presented in a future paper.

Mode 3. On the flight under discussion the spherical analyzer was operated in a third mode (see Figure 1), in which the voltage between grid 1 and the collector was varied in steps between 0 and 100 volts. From the resulting current voltage curves the assumptions made in the calculations of the required saturation voltage [*Sagalyn et al.*, 1963] can be tested. The voltage that must be applied between the electrodes for collection of all positive ions in the gas may be written

$$V = (E/e)[(b^2/a^2) - 1] \quad (3)$$

where E = energy of the most energetic ion in the gas striking grid 1 at grazing incidence, b = radius of grid 1, a = radius of the collector.

Mode 3 current voltage curves obtained at various altitudes on the Blue Scout flight are shown in Figure 3. At 617 km the saturation potential was measured to be 55 volts; using equation 3, and assuming a composition of 60 per cent O^+ , 40 per cent H^+ , it is calculated to be 50 volts. As shown in Figure 3, the saturation voltage was found equal to 33 volts at 1800

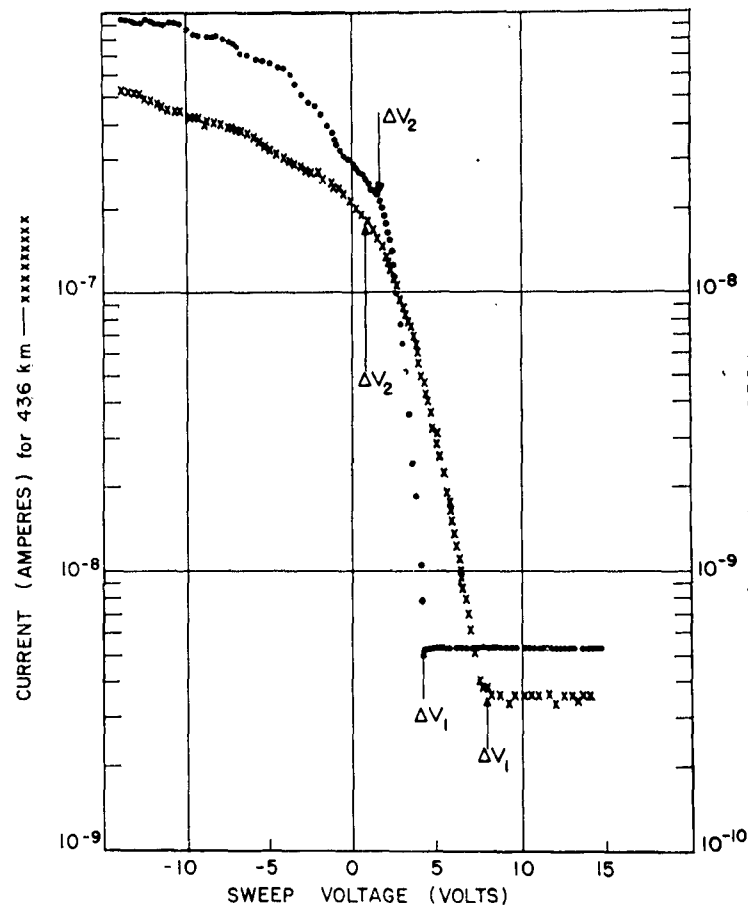


Fig. 2. Collector current versus sweep voltage applied to grid 1; mode 2; altitudes 436 and 1650 km.

km; it was calculated to be 28 volts assuming H^+ the dominant ion.

A differential energy distribution for charged particles in the gas is also obtained from these data.

RESULTS AND DISCUSSION

(a) Vertical Distribution

The vertical distribution of positive ions measured on the ascent and descent portions of a Blue Scout flight launched from Cape Canaveral on April 12, 1961, at 0107 EST is shown in Figures 4a and 4b. The maximum ion density is measured to be 2.25×10^5 ions/cm³ at 340 km on the descent. This is in good agreement with the ionosonde value of 2.4×10^5 electrons/cm³ measured at the nearest ionosonde station at

San Salvador. At 300 km on the descent, the latitude of the Blue Scout rocket is 2° south of the San Salvador station. The ionosonde data

TABLE 1. Altitude Variation of Rocket Potential V_r and $f(V)$

Altitude, km	$f(V)$	V_r , volts
300	0.98 ± 0.2	-1.4 ± 0.3
500	1.0	-1.3
700	1.0	-1.5
900	1.1	-1.4
1100	1.2	-1.5
1300	1.3	-1.8
1500	1.5	-2.0
1700	1.5	-2.2
1875	1.6	-2.1

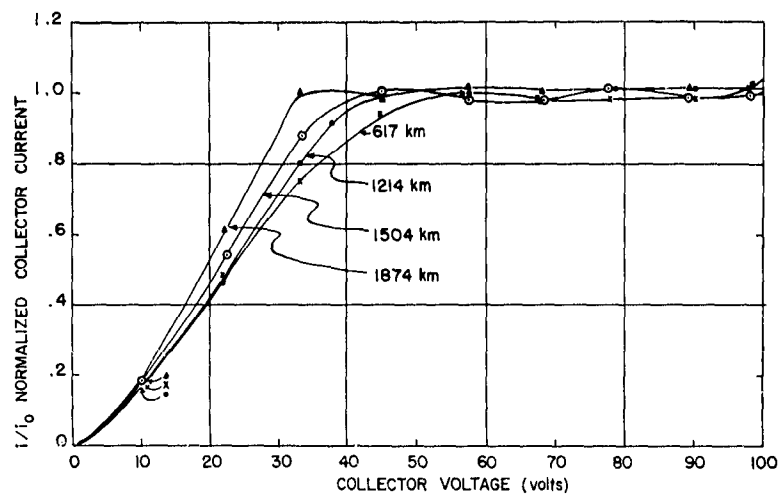


Fig. 3. Normalized collector current versus collector voltage at various altitudes.

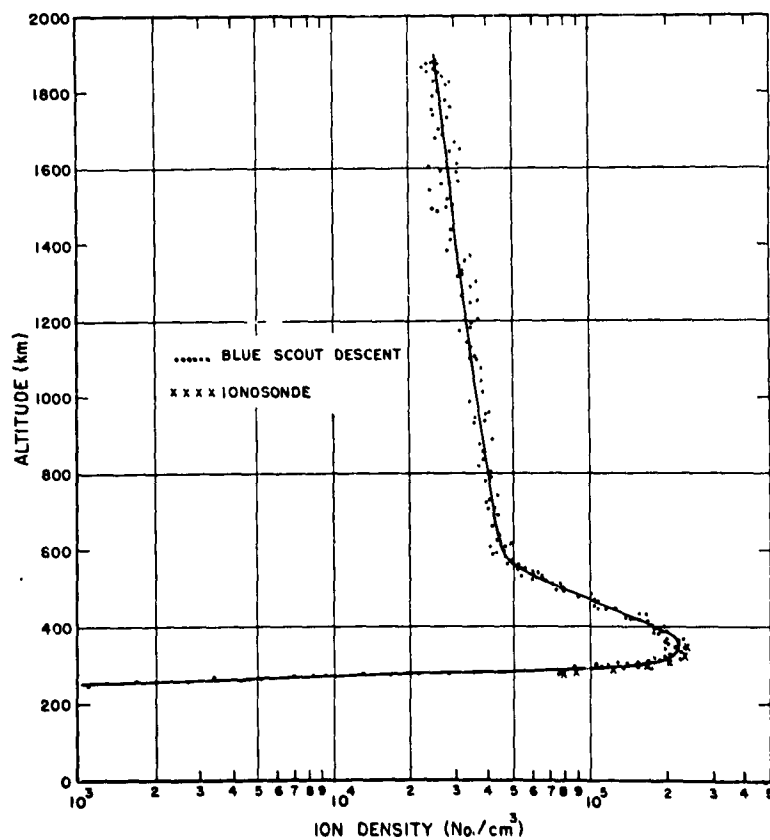


Fig. 4a. Altitude versus positive-ion density, Blue Scout flight, 0102 EST, April 12, 1961. Latitude 28°N, descent.

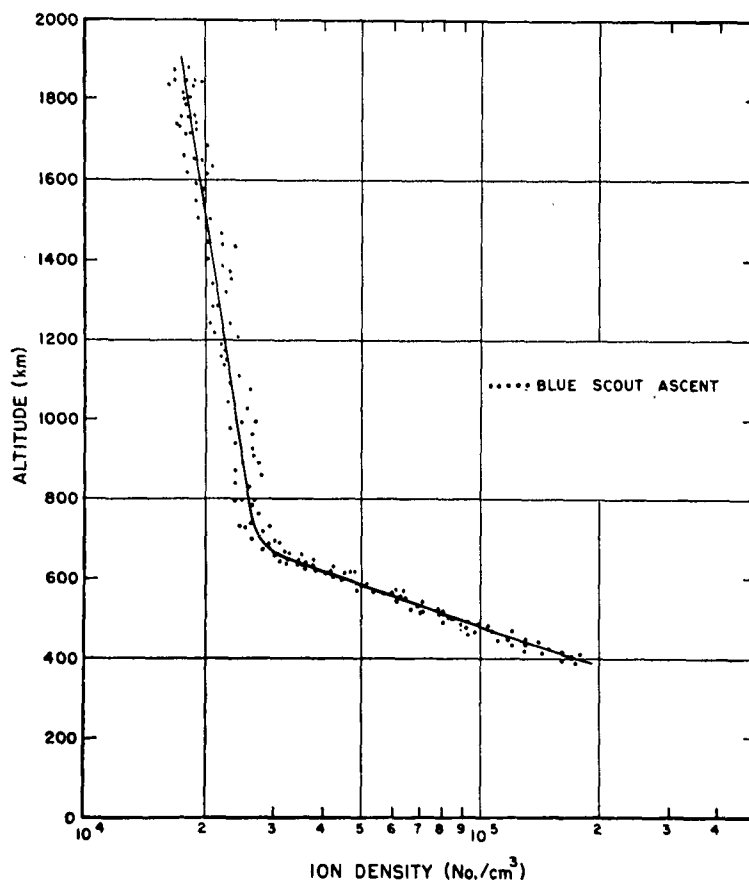


Fig. 4b. Altitude versus positive-ion density, Blue Scout ascent; ionosonde electron-density data obtained at latitude 28°N.

shown in Figure 4a were obtained from G. Stonehocker, of the National Bureau of Standards, Boulder, Colorado. A sharp change in the slope of the distribution is observed near 700 km on the ascent and 560 km on the descent portion of the flight. Above 600 km the descent values are about 30 per cent higher than the ascent values; below this level the ascent and descent values agree within 10 per cent. The difference between ascent and descent values should be small in the *F* region, since the total change in geomagnetic latitude for the *F*-region data is only 4°.

Above 700 km the vertical profiles differ significantly from other profiles recently presented [Hanson, 1962; Berning, 1960; Gringauz, 1962]. This will be discussed further in the next section. The results and discussion in (a), (b), and (c) were presented orally by Sagalyn *et al.* [1962].

(b) Ion Temperature, Average Ion Mass

Assuming diffusive equilibrium to exist above 300 km, the ion temperature is calculated from the hydrostatic equation for charged particles (equation 4) to be $1025 \pm 50^\circ\text{K}$ on the descent and $1100 \pm 50^\circ\text{K}$ on the ascent. Mange [1960] derived equation 4 assuming that the electron and ion temperatures are equal. The experimental observations of Evans [1962] indicate that this is a valid assumption for the nighttime *F* region. Brace *et al.* [1963] recently reported results of a nighttime flight in which the ascent and descent electron temperatures differed by 5 to 15 per cent in the altitude region 280 to 350 km. They indicated that this result implied that the electron and ion temperatures were not equal. Assuming their interpretation to be correct, the effect on the numerical solution of the

hydrostatic equation is negligible. On the basis of the measurements of *Istomin* [1960] it was assumed that O^+ was the dominant ion between 300 and 500 km.

Assuming the atmosphere to be isothermal above 500 km, the variation with altitude of the average ion mass and scale height can then be calculated [*Mange*, 1960]

$$\frac{d}{dz} \log_e n(z) = -\frac{g m_+(z)}{2kT} = -\frac{1}{H_i} \quad (4)$$

where

g = acceleration of gravity = $g_0 R^2 / (R + Z)^2$;

g_0 is the acceleration at R , the earth's surface.

k = Boltzmann's constant.

T = ion temperature.

$m_+(z)$ = average ion mass.

H_i = ion scale height.

$n(z)$ = total ion density at altitude Z .

The results obtained from the descent data are shown in Table 2. A rapid decrease in the average mass is found between 600 and 800 km; this is qualitatively indicated in the vertical profiles of Figure 4 showing a rapid change in slope in this region.

The diffusive equilibrium equation must be used with caution in the interpretation of daytime measurements, since it has been shown by the experimental work of *Spencer et al.* [1962] and *Brace et al.* [1963], and by the theoretical work of *Hanson* [1963] and *Dalgarno* [1963], that large differences can exist between the electrons and the gas temperatures in the lower F region during the day. These references also show, however, that the daytime electron and gas temperatures approach equality at about 330 km during quiet ionospheric conditions. The diffusive equilibrium equation should therefore be applicable above 330 km under quiet daytime conditions.

(c) Vertical Distribution of the Ionic Constituents

Dungey [1955] first discussed the distribution of charged particles in the earth's outer atmosphere under diffusive equilibrium conditions. *Mange* [1960, 1961], *Bauer* [1962, 1963], and *Hanson* [1962] have shown that if diffusive equilibrium exists information can be obtained about the distribution of the separate ionic con-

TABLE 2. Variation of Average Ion Mass $m_+(z)$ and Ion Scale Height with Altitude, Descent

Altitude, km	$m_+(z)$, amu	H_i , km
400	16	1.3×10^2
500	17	1.2×10^2
640	1.5	1.4×10^3
760	1.3	2.0×10^3
920	1.0	2.0×10^3
1000	1.2	2.0×10^3
1200	1.2	2.1×10^3
1400	1.1	2.4×10^3
1600	1.0	2.8×10^3
1875	1.1	2.7×10^3

* The accuracy of the values in this column is 15 per cent.

stituents from the measurement of the vertical profile of the total charge density. *Bates and Patterson* [1961, 1962] calculated the distribution of ionic species for model atmospheres containing two or three ionic species. Considerable interest in the experimental determination of ion composition above the F_2 peak has resulted from *Nicolet's* [1961] calculations which indicated that helium ions might be present in significant quantities in the earth's upper atmosphere.

Bauer [1962] solved the hydrostatic equation to obtain the altitude distribution for the total number of charged particles of a given sign in terms of geopotential altitude. *Hanson* [1962] integrated the equation for the ionic constituents and calculated the distribution of the individual ionic species, making estimates of the ion composition at a chosen reference level. Comparing his calculations with *Hale's* ion-density measurements, *Hanson* concluded that a helium layer approximately 2000 km thick must exist in the altitude range 1000 to 3000 km and that diurnal variations of this layer should be small. *Bourdeau et al.* [1962] concluded from the retarding potential analysis of a planar ion probe at 1650 km that the ratio He^+/O^+ was 1.5 for a daytime measurement.

In the analysis under discussion, the distribution of the ionic constituents above the peak of the F layer is obtained without making assumptions about a reference-level composition. Assuming diffusive equilibrium to exist for charged particles, the general expression for the concen-

tration of charged particles of a given sign $n(z)$ is written in terms of altitude, ion mass, and temperature. The relative proportions of the ionic constituents at a reference level are determined by comparing measured charge density distributions with solutions of the general expression for $n(z)$ for a wide range of reference-level compositions and temperatures. The composition and temperatures that are in best agreement with the experimentally determined profiles are used to solve exactly the hydrostatic equation for the individual ionic species. The procedure is applied to the results of the Blue Scout flight to obtain the altitude variations of O^+ , H^+ , and He^+ .

Assuming that the gas is electrically neutral, the general expression for the variation of total ion density with altitude is obtained from the integral form of the hydrostatic equation for charged particles. *Bauer* [1962] derived this expression in terms of geopotential altitude. It can also be obtained by summing over the expression of the individual ionic species derived by *Hanson* [1962]

$$n_+(z) = n_+(z_0) \left\{ \sum_i n_i(z_0) \left[\exp -\frac{g_0 m_i}{kT} \cdot \frac{R^2(z - z_0)}{(R + z)(R + z_0)} \right] / \sum_i n_i(z_0) \right\}^{1/2} \quad (5)$$

where $n_+(z_0)$ is the total concentration of positive ions at the reference altitude z_0 , m_i is the mass of the i th ionic constituent, $n_i(z_0)$ is the concentration of the i th constituent at the reference level z_0 . Equation 5 can be evaluated without knowledge of the individual ion densities $n_i(z_0)$ at the reference level, since

$$n_i(z_0) = \alpha_i(z_0) \sum_i n_i(z_0) \quad (6)$$

where $\alpha_i(z_0)$ is the relative abundance of the i th constituent at the reference height.

Substituting $n_i(z_0)$ given by equation 6 in the numerator of equation 5, the general expression for the charge density becomes

$$n_+(z) = n_+(z_0) \left\{ \sum_i \alpha_i(z_0) \exp -[g_0 m_i R^2 \cdot (z - z_0)/kT(R + z)(R + z_0)] \right\}^{1/2} \quad (5')$$

The dependence of this solution on temperature and ion composition is illustrated in Figures

5 and 6. In Figure 5 the solution of equation 5' is given for temperatures ranging between 800 and 1600°K and for two reference-level compositions: 0.5 per cent H^+ , 0.5 per cent He^+ , 99 per cent O^+ ; and 5.0 per cent H^+ , 0.0 per cent He^+ , 95 per cent O^+ . It is seen that the lower the temperature the more rapid the decrease of ion density with height. The magnitude of the decrease in charge density for a given temperature change varies considerably with the reference-level composition.

The dependence of the solution of equation 5' on composition is shown in Figure 6. The temperature is fixed at 1400°K while the proportions of the hydrogen, helium, and oxygen ion are varied. As is implied by equation 5', the greater the average ion mass at the reference level the more rapid the decrease in total ion density with height.

It is seen, therefore, that, if the temperature is known or can be independently determined, bounds can be placed on the composition at the reference level by comparing theoretical and experimentally determined distributions. The results of the Blue Scout flight are shown in Figure 7 in terms of $z - z_0$ with $z_0 = 425$ km for the ascent and 350 km for the descent data. N_0 is the total ion density at the reference level z_0 . The solution of equation 5' for the previously determined temperature of 1050°K—see section (b)—and varying composition at the reference level is shown in the same figure. It is seen that a reference-level composition of 5 per cent H^+ , 93.5 per cent O^+ , 1.5 per cent He^+ best fits the data. By means of perturbation techniques, a refined determination of the reference-level composition can be obtained taking the above result as first best guess. The analysis gives 5 ± 2 per cent H^+ , 94 ± 2 per cent O^+ , and He^+ between 0 and 1.5 per cent; 1.5 per cent represents an upper bound for the helium content at the reference level. Since the total ion concentration at the reference level was measured to be $1.35 \times 10^5 \text{ cm}^{-3}$, $H^+ = 6.75 \times 10^3 \text{ cm}^{-3}$ and $O^+ = 1.27 \times 10^5 \text{ cm}^{-3}$. The solution gives a value of $He^+ \leq 1 \times 10^3 \text{ cm}^{-3}$ at z_0 .

Ionic species. *Hanson* [1962] derived an expression for the i th constituent in terms of the reduced altitude z' . For purposes of computation it is more convenient to write this equation in terms of mass, temperature, and altitude above the surface of the earth:

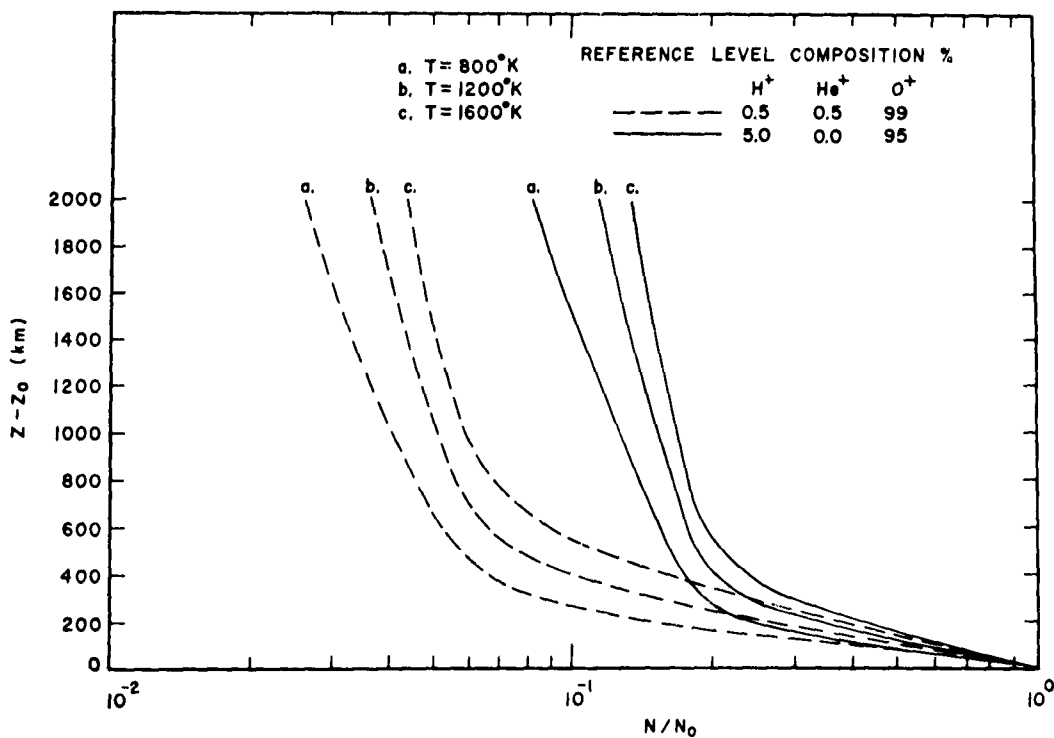


Fig. 5. Dependence of ion-density distribution on temperature for reference-level compositions of 0.5 per cent H^+ , 0.5 per cent He^+ , 99 per cent O^+ ; and 5 per cent H^+ , 95 per cent O^+ ; for temperatures ranging between 800 and 1600°K.

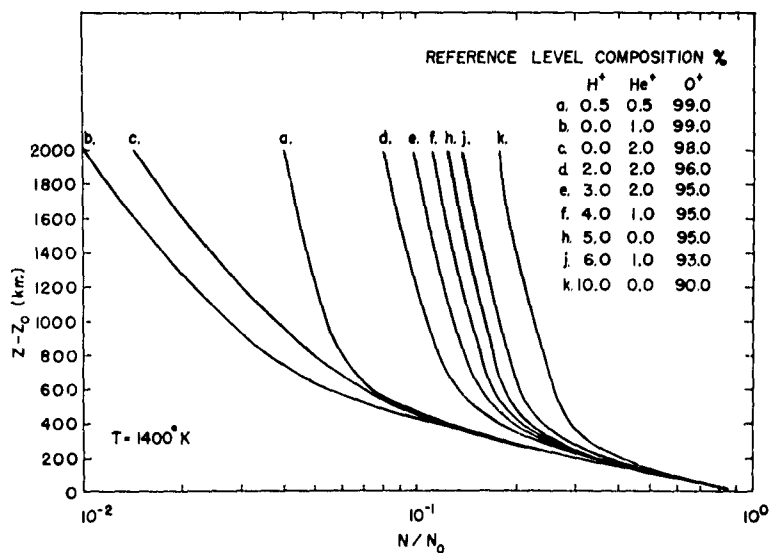


Fig. 6. Dependence of ion-density distribution on reference-level composition; $T = 1400^\circ\text{K}$.

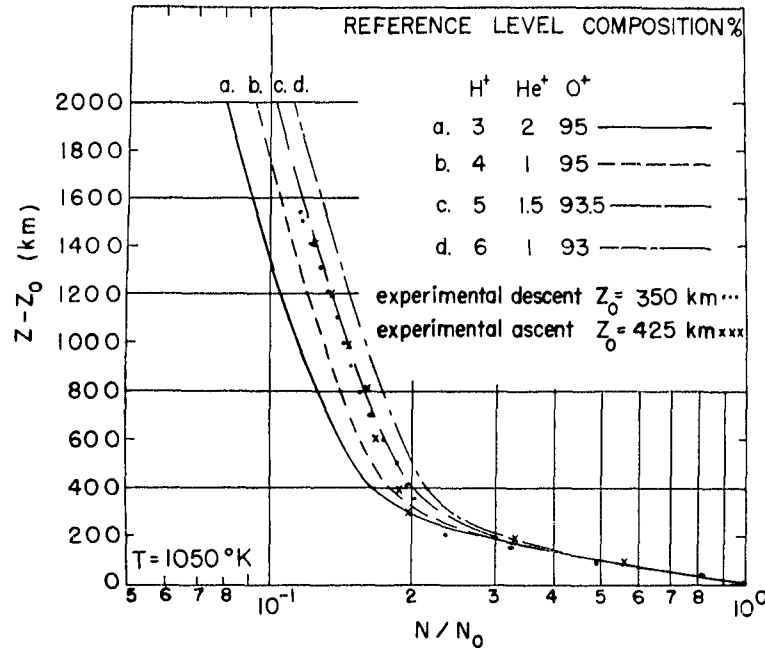


Fig. 7. Comparison of Blue Scout ascent and descent data with theoretical distributions calculated for $T = 1050^\circ\text{K}$ and varying reference-level composition.

$$n_i(z) = n_i(z_0) \left[\exp - \frac{g_0 m_i}{kT} \frac{R^2(z - z_0)}{(R + z)(R + z_0)} \right] \cdot \left[\frac{\sum_q n_q(z_0) / \sum_q n_q(z_0)}{\exp - \frac{g_0 m_q}{kT} \frac{R^2(z - z_0)}{(R + z)(R + z_0)}} \right]^{1/2} \quad (7)$$

Using the expression for $n_i(z_0)$ given by equation 6, the distribution of the ion species can also be written in terms of proportions of all constituents at the reference height.

$$n_i(z) = n_i(z_0) \left[\exp - \frac{g_0 m_i R^2(z - z_0)}{kT(R + z)(R + z_0)} \right] \cdot \left[\sum_q \alpha_q(z_0) \exp - \frac{g_0 m_q R^2(z - z_0)}{kT(R + z)(R + z_0)} \right]^{-1/2} \quad (7')$$

The dependence of the distribution of the ionic species given by equation 7' on temperature is shown in Figure 8 for a reference-level composition of 0.5 per cent H⁺, 0.5 per cent He⁺, 99 per cent O⁺, and temperatures varying between 800 and 1600°K. These curves show, as was first pointed out by Mange [1960, 1961],

that the distributions of the light ions will reach a maximum at some altitude above the reference level. It is seen that increasing temperature increases the altitude of maximum density for each constituent. Above the altitude of maximum density an increase in temperature decreases the rate of change of concentration of the i th ion with altitude; this relationship is reversed below the peak.

The effect of varying composition is seen in Figure 9a for the case of a fixed temperature of 1400°K. In Figure 9b normalized distributions are given for H⁺, He⁺, and O⁺, assuming the same proportions as in 9a and $T = 800^\circ\text{K}$. For fixed temperature and reference-level composition the altitude of peak density for each constituent increases with decreasing ion mass. Also, as shown in Figures 9a and 9b, the altitude of maximum density for a given ionic species increases with an increase in the average ion mass at the reference height. The curves of these figures have been given in terms of $n_i(z)/n_i(z_0)$. The absolute distribution of $n_i(z)$ can be obtained by multiplying results of the type given in the figures by $n_i(z_0)$, the experimentally determined density of the i th constituent

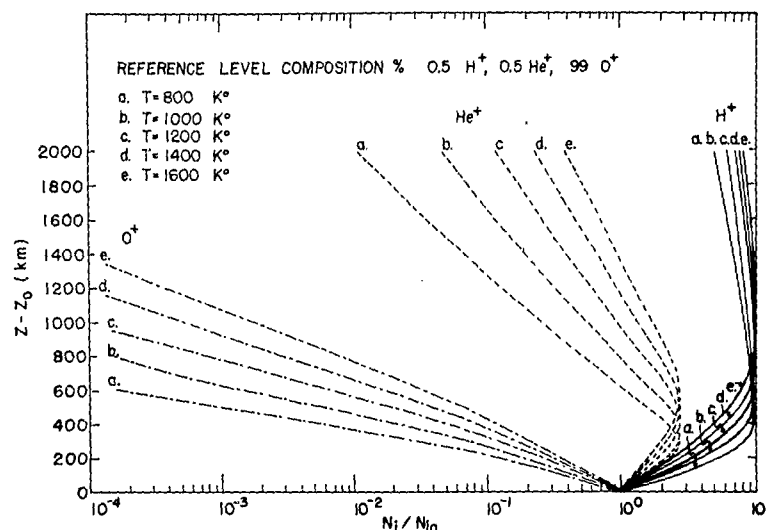


Fig. 8. Dependence of the vertical profiles of the ionic constituents O⁺, He⁺, and H⁺ on temperature under diffusive equilibrium conditions.

at the reference level. The shape of the distributions given in Figures 9 will not change; they will merely be shifted along the abscissa.

As indicated by equation 7' and by the results given in Figure 9, the scale height for a given species is a complicated function of temperature and ion composition at the reference level. The procedure outlined above provides a reliable method of determining the distribution of ions

above a reference level under conditions where diffusive equilibrium exists. The proportion of the various ionic constituents can be determined with an accuracy of about 15 per cent at the reference level. An upper bound can be given to the distribution of light ions with a relative abundance of 2 per cent or less at the reference level. The solution is not very sensitive to variations in composition of ions of mass greater than

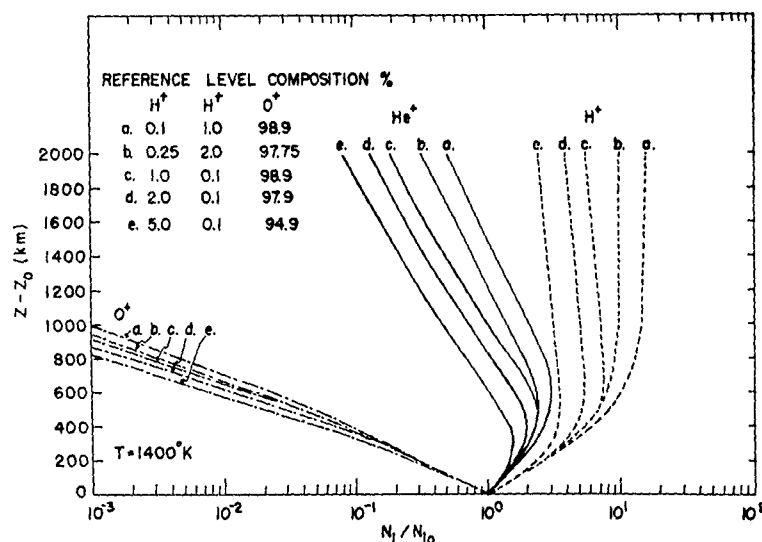


Fig. 9a. Dependence of the vertical profiles of the ionic constituents O⁺, He⁺, and H⁺ on reference-level composition for $T = 1400^\circ\text{K}$.

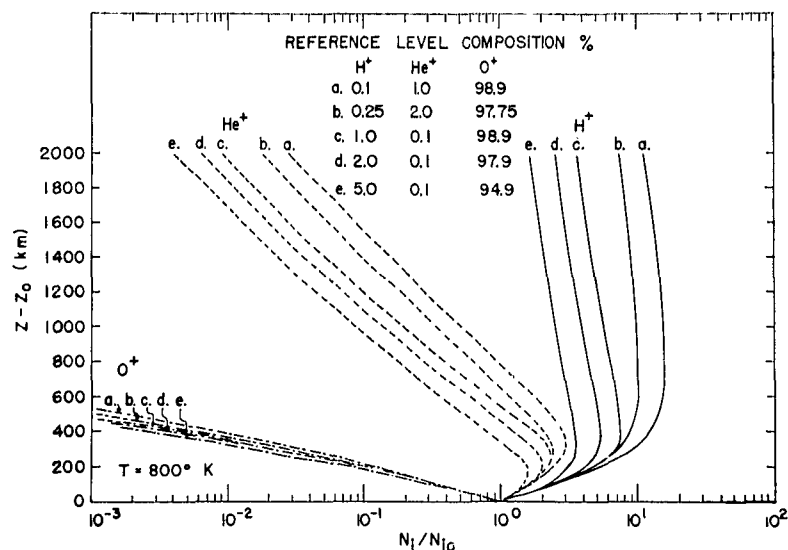


Fig. 9b. Dependence of the vertical profiles of the ionic constituents O^+ , He^+ , and H^+ on reference-level composition for $T = 800^\circ K$.

16 amu, since the relative concentrations of heavier species are already small and continue to decrease with altitude.

The distributions of hydrogen, oxygen, and helium ions obtained from equation 7' upon substituting the temperature and composition values derived above for the Blue Scout flight are shown in Figure 10; maximum values for

the helium-ion distribution deduced from these experimental data are shown as curve *b*; He^+ curve *a* is the distribution obtained for 1 per cent He^+ at the reference level.

These results show that H^+ becomes the dominant ion at 650 km and that the maximum in its distribution occurs at 750 km. The helium-ion concentration reaches a maximum at 625

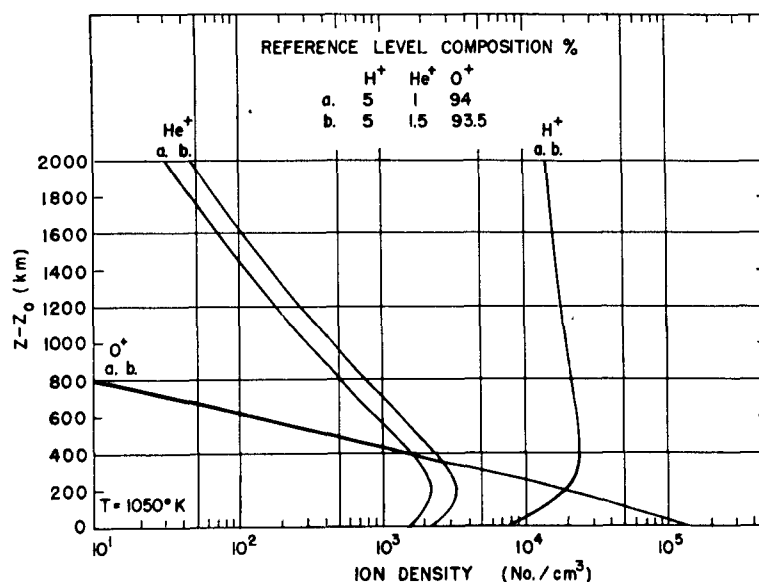


Fig. 10. Distribution of O^+ and H^+ with altitude and the upper limit for the He^+ distribution obtained from the Blue Scout results.

km, 200 km above the reference level, and is never the dominant ion. This result differs considerably from the conclusions of *Hanson* [1962] and *Bourdeau et al.* [1962] from the analysis of daytime measurements. They are in good agreement, however, with the results of other nighttime measurements. On the same nighttime Blue Scout flight discussed here *Ulwick and Pfister* (private communication, 1963) measured electron densities by means of an impedance probe experiment, the results of which are in good agreement with our positive ion density measurements. The only significant difference in the data from the two experiments occurs below 300 km on the descent. It is due to the fact that the minimum sensitivity of their experiment was approximately $1.5 \times 10^4/\text{cm}^3$. The profile of electron densities given by *Ulwick and Pfister* [1963, Figure 9] is a composite of the ascent and descent impedance probe data obtained on the Blue Scout flight and p-f records. *Donley* [1963] reported results of nighttime positive ion density measurements to 2700 km obtained with a planar electrostatic probe which are also in good agreement with the results presented here. Preliminary analysis of ion mass spectrums from the Ariel satellite [*Willmore et al.*, 1963] shows large differences from night to day in the mass of the dominant ion above the peak of the *F* region consistent with the results of the analysis of day and nighttime ion- and electron-density profiles.

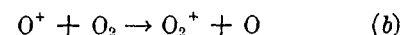
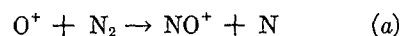
The experimental results and the analysis indicate that helium ions must be present in greatly varying amounts in the lower exospheres, the distribution being highly dependent on the temperature and relative concentrations of all the ions present. This is in agreement with the conclusions of *Bauer* [1963] and *Bourdeau and Bauer* [1963] as to the temperature dependence of the helium-ion distribution. It should be noted, however, that their analysis is based on a special solution of the diffusive equilibrium equation obtained by assuming that there is a transition level where the concentrations of two ionic species are equal. This assumption is not implied by the general equation (equation 5).

Taylor et al. [1963], for example, measured a helium-ion peak at about 600 km and concluded on the basis of *Bauer's* analysis that diffusive equilibrium did not exist, since the

maximum occurred below the predicted transition level. Using reference-level values obtained from *Taylor's* data at 450 km, the general theory predicts a broad helium distribution with a maximum at about 850 km in reasonable agreement with *Taylor's* experimental results.

(d) Ion-Atom Interchange Coefficients

The determination of the rate coefficients for the processes by which ionized atomic oxygen may be destroyed is important to the understanding of the decay of the nighttime *F* region. At present there is a significant disagreement between the values deduced from theory, laboratory experiments, and ionospheric data for the ion-atom interchange reactions considered important to the loss of O^+ at night [*Bates and Nicolet*, 1960]:



The theoretically determined rate coefficients for reactions *a* and *b* are of the order of $10^{-12} \text{ cm}^3 \text{ sec}^{-1}$ [*Field et al.*, 1957; *Gioumousis and Stevenson*, 1958]. *Langstroth and Hasted* [1962] obtained a laboratory value of the rate coefficient k_1 for reaction *a* above of $4.7 \times 10^{-12} \text{ cm}^3 \text{ sec}^{-1}$. *Sayers and Smith* [1963] reported a laboratory value of $2.7 \times 10^{-11} \text{ cm}^3 \text{ sec}^{-1}$. *Talrose et al.* [1962] gave an upper limit to k_1 of $6.7 \times 10^{-12} \text{ cm}^3 \text{ sec}^{-1}$. *Galli et al.* [1963] published a value of $k_1 = 2.2 \times 10^{-11}$. Using the *Johnson et al.* [1958] ion composition data obtained from rockets, *Bates and Nicolet* [1960] deduced a value of $k_1 + 0.1 k_2 \cong k_1 = 1.3 \times 10^{-12} \text{ cm}^3 \text{ sec}^{-1}$. *Yonezawa et al.* [1959] obtained a value of $k_1 = 3 \times 10^{-12} \text{ cm}^3 \text{ sec}^{-1}$ from upper atmosphere data assuming steady-state conditions.

Using both the Blue Scout ion-density profiles and local electron-density distributions provided by G. Stonehocker of the National Bureau of Standards, Boulder, Colorado, the ion-atom interchange coefficient k_1 for process *a* has been evaluated at 280 and 300 km from data obtained between 2030 and 0300 A.M.

It was assumed that at night in this altitude range there are no significant sources of ionization. The atomic oxygen ion concentration may change as a result of radiative recombination, as a result of ion-atom interchange with N_2 , O_2 , and NO , and by diffusion. Because the NO con-

centration is a few orders of magnitude lower than the molecular nitrogen and oxygen concentrations, it is assumed that the loss of O^+ by ion-atom interchange with NO can be neglected. In the altitude region 280 to 300 km, *Istomin's* [1960] results show that O^+ contributes more than 95 per cent to the total positive-ion concentration; O^+ is therefore assumed equal to the electron density, n . The rate of change of O^+ must then be approximately equal to the rate of change of the electron density with time. This may be expressed

$$\frac{dn}{dt} = \alpha n^2 + k_1 N_2 n + k_2 O_2 n + \text{div}(nV) \quad (8)$$

Dividing equation 8 by $N_2 n$,

$$\gamma = \left(k_1 + k_2 \frac{O_2}{N_2} \right) = \left[\frac{dn}{dt} - \alpha n^2 - \text{div}(nV) \right] / N_2 n \quad (9)$$

k_1 and k_2 are the same order of magnitude, and, since O_2/N_2 is approximately 6×10^{-3} , $\gamma \approx k_1$. A summary of the calculated and measured quantities used in the evaluation of γ is given in Table 3. $dn/dt \approx dO^+/dt$ was evaluated using the Blue Scout data and local ionosonde electron-density profiles for the night of April 11-12. The values given in Table 3, columns 2 and 4, are time averages for the periods shown. α was taken equal to $1.3 \times 10^{-13} \text{ cm}^3 \text{ sec}^{-1}$ [Bates *et al.*, 1939]. The divergence term may be writ-

ten [Ferraro, 1946; Martyn, 1955; Dungey, 1956; Ratcliffe and Weekes, 1960]:

$$\text{div}(nV) = D_a \sin^2 I \left[\frac{d^2 n}{dz^2} + \frac{3}{2H} \frac{dn}{dz} + \frac{n}{2H^2} \right] \quad (10)$$

where

I = magnetic dip angle at position of measurement.

$D_a = 4.6 \times 10^{-21} T/N \text{ cm}^2 \text{ sec}^{-1}$, the ambipolar diffusion coefficient [Dalgarno, 1961].

T = temperature, $^{\circ}\text{K}$.

N = the neutral particle density cm^{-3} . *U. S. Standard Atmosphere* [1962] densities were corrected for local time and solar flux conditions.

z = altitude, km.

H = neutral scale height.

The values of n and its first and second derivatives were obtained from the ion- and electron-density profiles. It should be noted that the calculations show that diffusion acts as a source below 300 km and changes sign slightly above 300 km.

The values of N_2 and O_2 were based on the work of Harris and Priester [1963] for a value of the 10.7-cm solar flux of 89 watts/meter² cps. A small correction to their values was provided by K. Champion (private communication, 1963). As shown in Table 3, column 7, k_1 is found to vary between 2 and $4 \times 10^{-12} \text{ cm}^3 \text{ sec}^{-1}$. There

TABLE 3. Calculated Values of Ion-Atom Interchange Coefficients (column 7)
NO⁺ Production Rates (column 8)

1 Altitude, km	2 n , no./cm ³	3 N_2 , no./cm ³	4 dn/dt , cm ⁻³ sec ⁻¹	5 αn^2 , cm ⁻³ sec ⁻¹	6 $-\text{div}(nV)$, cm ⁻³ sec ⁻¹	7 γ , cm ³ sec ⁻¹	8 $k_1 O^+ N_2$, cm ⁻³ sec ⁻¹
Time: 2030-2100							
280	3.9×10^5	9.9×10^7	55	0.2	34	2.3×10^{-12}	89
300	4.4×10^5	5.9×10^7	44	0.25	8	2.0×10^{-12}	52
Time: 2100-0100							
280	2.6×10^5	8.4×10^7	16	0.1	31	2.1×10^{-12}	46
300	3.1×10^5	4.8×10^7	15	0.1	15	2.0×10^{-12}	30
Time: 0100-0300							
280	1.2×10^5	6.8×10^7	9	0.02	24	4.0×10^{-12}	32
300	1.9×10^5	3.8×10^7	8	0.05	20	3.9×10^{-12}	28

is an uncertainty of about a factor of 2 in these calculations. Nisbet and Quinn [1963] deduced a value from the loss coefficient $\beta = 9 \times 10^{-10}$ sec⁻¹ for $T = 1050^\circ\text{K}$ at 300 km from a statistical analysis of ionosonde data. Substituting a value of $N_2 = 4.8 \times 10^7/\text{cm}^3$ ($T = 1050^\circ$) from Table 3 leads to a value of $k_1 = 1.6 \times 10^{-12}$ cm³ sec⁻¹. Since laboratory experiments in general provide an upper limit for the rate coefficients, the results obtained from the laboratory and upper atmospheric data are in reasonably good agreement. It was pointed out earlier that nighttime sources of ionization have been neglected in these calculations. Hinteregger (private communication, 1963) has estimated that the contribution of corpuscular radiation to ion-pair production in the F region could not be greater than 10 per cent of the daytime solar ultraviolet flux. Including this ion pair production rate in the above calculations increases the value of the ion-atom interchange coefficient k_1 by a factor of 2.

The rate of formation of NO^+ by ion-atom interchange process a , assuming for k_1 the values given in Table 3, column 5, gives production rates varying between 28 and 89 per cm³ sec⁻¹ (column 8). The production rate decreases with time largely because of time variations of the O^+ concentration. This represents an irreversible loss of nitrogen from the upper atmosphere.

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