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PLANETARY AERONOMY XII: THE ROLE OF INTERPLANETARY DEBRIS IN PLANETARY ATMOSPHERES: I. SODIUM IN THE EARTH'S ATMOSPHERE

F. F. MARMO H. K. BROWN

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PLANETARY AERONOMY XII:
THE ROLE OF INTERPLANETARY DEBRIS IN PLANETARY ATMOSPHERES: I. SODIUM IN THE EARTH'S ATMOSPHERE

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I. INTRODUCTION

Interplanetary debris can be deposited in planetary atmospheres by vaporization processes brought about by the interaction of these particles with the ambient atmosphere. It is possible that these deposited chemical species can play a significant role in the aeronomy of the upper atmospheres of the terrestrial planets Venus, Earth and Mars. However, in spite of this potential, it appears that little or no detailed investigations have been directed toward this problem as far as the planets Venus and Mars are concerned. This is probably due to at least two factors: first, the aeronomy of the Martian and Venusian planets is not well known; and second, even in the Earth atmosphere the problem is not well understood since some contraversy still prevails concerning the origin of atmospheric sodium observed in the twilight and airglow. Specifically, both terrestrial (marine)(1,2) and extraterrestrial (meteoric and micrometeoric debris)(3) origins have been favored. Clearly, investigations into other planetary atmospheres are only justified on the basis of accepting the extraterrestrial origin.

In a recent article, Junge et al.(3) considered various origins for the atmospheric sodium observed above 70 km, and offered some convincing arguments to show that all terrestrial sources seem unlikely, including sea salt. Of the extraterrestrial sources considered, Junge has shown that the meteoric influx provides sufficient quantities to account for the observed sodium. In addition, they point out that the mass influx due to micrometeorite material is considerably greater than that due to meteors. However, owing to the difficulty of estimating the fraction of incoming micrometeorite material that vaporizes, they were unable to make an accurate estimate of the contribution from this component. As a compromise, they suggest that the meteors and micrometeorites deposit equal amounts of sodium atoms in the Earth's upper atmosphere. They conclude that a flux of about $3\text{x}10^4$ Na atoms/cm^2-sec can be employed as a working value, but also state that this value could be off by as much as two orders of magnitude. For the purposes of the present report, an extraterrestrial source is accepted and the role of the corresponding debris in the Earth, Venus and Mars atmospheres is investigated.

In this preliminary analysis, sodium in Earth atmosphere is examined first in order to check the validity of the model and of the parameters chosen. Then, with identical debris influx rates assumed for Venus and Mars, the distribution of sodium is calculated for their atmospheres. All the computations are presented on a relative scale for ready comparison since at this stage, only comparisons between the various planets are attempted. It is emphasized that the present effort is somewhat conjectural, so that the results should be applied with appropriate caution. However, certain qualitative features have become evident by this work which serve as a basis for further investigation.

II. QUALITATIVE DISCUSSION OF THE PROBLEM

Before any technical discussion is given, it is appropriate to give a qualitative description of the over-all problem as will become evident by the following. At first sight, it may seem premature to wonder about the role of interplanetary debris in planetary atmospheres other than Earth. Perhaps this is so, but on the other hand, a rather considerable potential exists as far as any optical probing or radar probing of these planets is concerned. For example, it can be shown that under certain conditions, the atmospheres would be easily optically thick in terms of several meteoric components and also that ionospheric electron number densities $> 10^8$ electrons cm^{-3} can be achieved at least in principle. Qualitative arguments are now given to justify these remarks.

Recent mass spectrometric(4) and twilight optical(5,6) measurements have verified the presence of Mg^+ and Ca^+ in the Earth's upper atmosphere. The mass spectrometric measurements were achieved during a meteoric shower and indicated that the Mg^+ and Ca^+ were distributed between 100 and 110 km with a maximum number density of about 10^4 cm^{-3} for Mg^+ and about $5x10^2$ cm^{-3} for Ca^+. In addition, Nagy(7) has recently reported the mass spectrometric measurement of Na^+ between 90 and 120 km, but no values were given for the sodium ion number density. These measurements show that the number density of meteoric debris ions are not insignificant when compared to the ion densities of other Earth ionosphere components. It is not only possible but almost a certainty that without the presence of atmospheric oxygen, these debris ions would, indeed, become the dominant species in the Earth atmosphere. This can be justified on the basis of previous work by Marmo(8) in which he describes the results of a series of rocket seeding experiments where Na, K, and Cs (debris-like) were ejected into the Earth upper atmosphere for the express purpose of generating highly dense artificial ionospheres. The experiments have shown that atmospheric molecular oxygen, O_2, is the dominant factor in precluding the generation of long-lived, dense ($> 10^7$ electrons cm^{-3}), artificial ionospheres at altitudes below 100 km. This was due to two factors involving molecular oxygen: (a) the high chemical consumption probability per alkali atom, and (b) the efficient formation of negative ions (O_2^-) with the subsequent removal of the alkali ion via mutual neutralization.

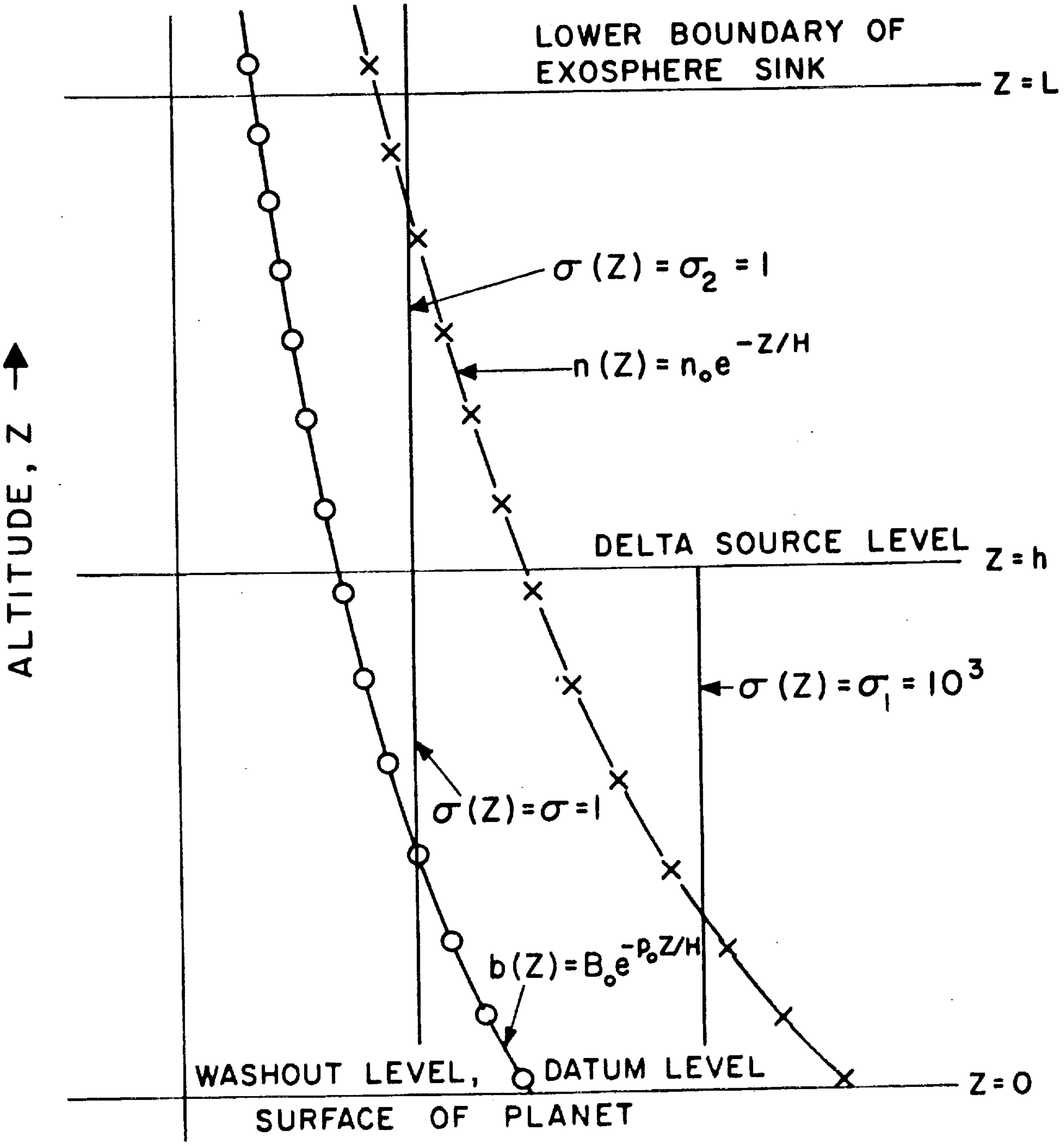
Although the absolute oxygen content in the atmospheres of the planets Venus and Mars has not as yet been established, there seems little doubt that oxygen is at best only a minor constituent. It can be shown that if, indeed, the atmospheres of Venus and Mars were truly oxygen-free, extremely dense ionospheres could be generated via solar photoionization of meteoric debris atoms and in addition, the atmospheres would be optically thick for several species. On the other hand, the present work will show that solar photodissociation of CO_2 in these atmospheres produces sufficient O_2 to act as an effective buffer against the excessive buildup of free atoms. In particular, it will be shown that within the limitations of the present model, the debris atom number density-altitude distributions are somewhat similar to those for the Earth atmosphere. On the other hand, some marked differences are observed and point up the need for further investigation.

III. TECHNICAL DISCUSSION OF THE PROBLEM

The first calculations were performed for the Earth atmosphere. This was done in order to check the validity of the model, boundary conditions, and parametric values employed. Following this, calculations were performed for the planets Venus and Mars so that cogent comparisons could be made between the three terrestrial planets.

A. PHYSICAL-MATHEMATICAL MODEL

The physical-mathematical model employed was chosen to reflect the physical setup schematically shown in Figure 1. For the case of the Earth, it is presumed that atomic sodium is deposited at a single altitude of 105 km so that a delta source level is defined. Against this steady source, sinks are considered: an exospheric sink above the source level, a chemical sink below the source level, and the sink at the planet surface. In Fig. 1, the lower boundary of the exosphere sink is indicated at an altitude, $z = L$, and the chemical sink is indicated by the curve labeled $b(z) = B_o \exp(-p_o z/H)$. Concerning diffusion, two cases are considered: (a) Case I in which molecular diffusion ($\sigma_2 = 1$) prevails above the source level, whereas below the source level, eddy diffusion prevails ($\sigma_1 = 10^3$); and (b) Case II in which molecular diffusion prevails above and below the source level so that $\sigma_1 = \sigma_2 = 1$.



SCHEMATIC OF GENERAL PHYSICAL SET UP FOR ANY ONE OF THE TERRESTRIAL PLANETS

Figure 1

The proper mathematical model is suggested by the well-known Lettau$^{(9)}$ equation

$$n_s \bar{c}_s = - n d_o \left\{ \frac{\bar{\nabla} \nu_s}{Q_s} - \nu_s \left[\mu_s \bar{\nabla} (\ell n \; p) - \frac{m\bar{f}_s}{kT} \right] \right\} + n\nu_s \bar{V} \qquad (1)$$

which describes the mass transport of a minor constituent in a planetary atmosphere.

For our purposes, the vertical transport of the debris constituent in the isothermal atmosphere can be considered free of regular flow $(\bar{V} \equiv 0)$ and external body forces $(\bar{f}_s \equiv 0)$, other than gravity. In addition, at present, only a steady state solution is required; thus, Eq. (1) can be written as

$$Q_s(z) = - n_o \, d_o \left[\sigma(z) \, \frac{d\nu_s(z)}{dz} + \frac{\mu_s}{H} \, \nu_s(z) \right] . \qquad (2)$$

This equation defines the vertical transport flux $Q_s(z)$, particles per square centimeter per second, of the debris constituent at the height z (km) above the datum level z=0, in an isothermal atmosphere, in which the ambient number density n(z), particles/cm^3, is defined by the exponential law

$$n(z) = n_o \, e^{-z/H} \quad , \qquad n_o = n(0) \quad ,$$

and where H (km) is the atmospheric pressure scale height. The specific concentration is given as

$$\nu_s(z) = \frac{n_s(z)}{n\;(z)} \qquad (3)$$

of the minor constituent of number density $n_s(z)$, particles/cm^3, at the height z.

The quantity

$$\sigma(z) = \frac{D(z) + d(z)}{d(z)} \tag{4}$$

where

$$d(z) = d_o \, e^{z/H} \ , \qquad d_o = d(0) \ , \tag{5}$$

is the molecular diffusion coefficient and D(z) is the eddy diffusion coefficient.

The quantity,

$$\mu_s = \frac{m_s - m}{m} \ , \tag{6}$$

is the relative weight factor where m_s and m are the masses of the minor constituent (debris atom) and ambient atmospheric species, respectively.

The space gradient, dQ_s / dz, of the vertical transport flux, Q_s, satisfies the equation of continuity

steady state vertical flux gradient = delta source - chemical sink - exospheric sink

or

$$\frac{dQ_s}{dz} = S^{(+)}(z) - S_o^{(-)}(z) - S_L^{(-)}(z) \ . \tag{7}$$

Thus, the delta source

$$S^{(+)} \equiv N_o \, \delta \quad \begin{aligned} &= f_o \ , \quad |z - h| < \epsilon \\ &= 0 \ , \quad |z - h| > \epsilon \end{aligned} \ , \quad \lim_{\epsilon \to 0} 2\epsilon \, f_o = N_o \ , \tag{8}$$

of minor constituent particles of strength N_o (particles/cm^2-sec), located at the fixed height z=h above the datum level z=0. $S_o^{(-)}$ is the steady, chemical consumption function,

$$S_o^{(-)} = b(z)\ n(z) \qquad \text{(particles/cm}^2\text{-sec)} \tag{9}$$

where

$$b(z) = B_o\ e^{-p_o z/H} \qquad (\text{sec}^{-1}) \tag{10}$$

is the probability of a chemical reaction at the height z. The exosphere exponential sink function is defined as

$$S_L^{(-)} \begin{array}{ll} = 0 & 0 < z < L \\ = B_L\ e^{-p_L z/H}\ , & z > L \end{array} \quad , \quad \text{(particles/cm}^2\text{-sec)} \tag{11}$$

where z=L is the lower boundary of $S_L^{(-)}$.

The detailed calculations for obtaining the closed analytic solutions are not repeated here. However, a brief sketch of the method of attack is included for completeness.

First, the following substitutions are made:

$$x = \frac{1}{q} \exp\left[- \frac{(1+p_o)}{2} \frac{z}{H} \right] \quad , \tag{12a}$$

$$\nu = q^{-1/q}\ x^{-\frac{1}{2}q}\ V \quad , \tag{12b}$$

and

$$2q = -\ (1+p_o)\ \frac{\sigma}{\mu_s}\ , \quad \text{where} \quad \mu_s < 0 \quad \text{and} \quad \sigma = \text{constant} \geqq 1. \tag{12c}$$

Now the H. Lettau vertical transport flux formula in Eq. (2) takes the form

$$Q_s(z) = -\frac{n_o d_o \mu_s}{2H} q^{-1/q} x^{-\frac{1}{2}q} \left[2qx \frac{dV(x)}{dx} + V(x) \right] \quad , \tag{12'a}$$

and the equation of continuity, as defined by Eq. (7), in the ν_s, z domain, is transformed into the modified Bessel differential equation,

$$L\,V \equiv \frac{d^2V}{dx^2} + \frac{1}{x}\frac{dV}{dx} - \left(c^2 + \frac{1}{4q^2x^2}\right) V = 0 \quad , \tag{12'b}$$

where

$$c^2 = \frac{\sigma B_o H^2}{d_o \mu_s^2} \quad , \quad \mu_s < 0 \quad , \qquad \sigma = \text{constant} \geqq 1 \quad , \tag{12'b'}$$

in the V,x domain.

The discontinuity of the flux function Q_s at the delta source level, z=h:

$$Q_s(h+0) = Q_s(h-0) + N_o \quad , \tag{13}$$

due to the presence of the delta source $N_o\delta(z,h)$ at z=h, and the piecewise definition of the step function $\sigma(z)$,

$$\sigma(z) \begin{array}{ll} = \sigma = \sigma_1 = \text{constant} \geqq 1 \ , & 0 < z < h \qquad (14a) \\ = \sigma = \sigma_2 = \text{constant} \geqq 1 \ , & z > h \quad , \qquad (14b) \end{array}$$

require that the V,x domain be composed of two domains, V_1, x_1 and F_2, x_2 , where

$$V(x) \equiv V_1(x_1) \quad , \quad x = x_1 \quad \text{for all } z \text{ in } 0 < z < h \tag{15a}$$

and

$$V(x) \equiv V_2(x_2) \ , \quad x = x_2 \quad \text{for all } z > h. \tag{15b}$$

It is assumed that the lower boundary $z = L > h$ of the exosphere exponential sink function $S_L^{(-)}$, listed in Eq. (11), is so far removed from the delta source level, $L \gg h$, that for all practical purposes, L may be considered located at infinity: $L \approx \infty$ (if not, the V-x domain V,x would consist of three sub-domains).

The resolution of the boundary value problem in the V,x domain, which consists of the following set of conditions:

$$L\,V_1 = 0 \qquad \text{and} \qquad L\,V_2 = 0 \tag{16a}$$

$$\nu_s \to 0 \quad \text{as} \quad z \to 0 \ , \qquad \nu_s < M \quad \text{as} \quad z \to \infty \ , \tag{16b}$$

and

$$\nu_s\,(h{+}0) = \nu_s(h{-}0) \ , \qquad Q_s(h{+}0) = Q_s(h{-}0) + N_o \ , \tag{16c}$$

requires the determination of the pair of constants (A_1,B_1), and (A_2,B_2) in the general solutions,

$$V_1(x_1) = A_1\, I_{\frac{1}{2}q_1}\,(c_1x_1) + B_1K_{\frac{1}{2}q_1}\,(c_1x_1) \tag{17a}$$

and

$$V_2(x_2) = A_2\, I_{\frac{1}{2}q_2}\,(c_2x_2) + B_2K_{\frac{1}{2}q_2}\,(c_2x_2) \ , \tag{17b}$$

of the modified Bessel differential equations listed in Eq. (16a) of the boundary value problem, wherein

$$I_{\frac{1}{2}q}\ (cx) \qquad \text{and} \qquad K_{\frac{1}{2}q}\ (cx) \qquad (17')$$

are the modified Bessel functions, of order $\frac{1}{2}q$, of the first and second kind, respectively.

The boundary value problem stated in Eqs. (17) was evaluated for the terrestrial planets for Cases I and II with the parameter-values specified in Table 1.

1. Discussion of Parameter Values

Most of the parametric values included in Table 1 require no comments; however, some discussion is required to justify the choices for values of the following parameters: (a) delta source level, (b) lower boundary of exosphere sink, and (c) the chemical consumption probability per sodium atom.

a. Altitude Choice for Delta Source Levels of Earth, Venus and Mars

Undoubtedly, a more realistic source function is available by employing a Gaussian distribution of a specified halfwidth with maximum deposition at some selected altitude. However, for the present formulation, it is mathematically difficult to incorporate this source function, whereas the use of a delta source function made the problem tractable. The choice of a single deposition altitude is not only somewhat unrealistic, but also points up the problem of the proper choice for this altitude. It seems reasonable to consider this problem first for the planet Earth, and then

TABLE 1

PARAMETERS AND VALUES EMPLOYED IN CALCULATIONS FOR THE ATMOSPHERES OF EARTH, VENUS, AND MARS

Parameter	Earth-Value	Venus-Value	Mars-Value
delta source level, h	105 km	192 km	270 km
lower boundary of exospheric sink, L	∞	∞	∞
mass Na atom/mean mass ambient, m_s/m	2/3	2/3	2/3
total number density at surface, n_o	$2.5\text{x}10^{19}\text{cm}^{-3}$	$6.6\text{x}10^{20}\text{cm}^{-3}$	$2.7\text{x}10^{18}\text{cm}^{-3}$
pressure scale height, H	6.6 km	6.7 km	20 km
local number density, n(z)	$n_o \exp(-z/H)$	$n_o \exp(-z/H)$	$n_o \exp(-z/H)$
molecular diffusion coefficient at surface, d_o	$1.8\text{x}10^{-1}\text{cm}^2/\text{sec}$	$6.7\text{x}10^{-3}\text{cm}^2/\text{sec}$	$1.6\text{x}10^{0}\text{cm}^2/\text{sec}$
local molecular diffusion coefficient, d(z)	$d_o \exp(-z/H)$	$d_o \exp(-z/H)$	$d_o \exp(-z/H)$
σ-value for region below delta source level	$\sigma_1=10^3$ (for Case I) $\sigma_1=1$ (for Case II)	$\sigma_1=10^3$ (for Case I) $\sigma_1=1$ (for Case II)	$\sigma_1=10^3$ (for Case I) $\sigma_1=1$ (for Case II)
σ-value for region above delta source level	$\sigma_2=1$ (for Case I) $\sigma_2=1$ (for Case II)	$\sigma_2=1$ (for Case I) $\sigma_2=1$ (for Case II)	$\sigma_2=1$ (for Case I) $\sigma_2=1$ (for Case II)
consumption probability/Na atom, b(z)	$4.8\text{x}10^{10}\exp(-2.2z/H)$	$4.0\text{x}10^{10}\exp(-2.3z/H)$	$1.0\text{x}10^{5}\exp(-2.3z/H)$

extrapolate for the other planets. This is what was done in the present case in which the Earth-value of 105 km was obtained in the following manner.

Herlofson(10) determined the following equation to describe the rate of vaporization of meteoric materials at any point along the trail:

$$q = 9/4q_{max}(P/P_{max})[1 - 1/3(P/P_{max})]^2 \tag{19}$$

where

q_{max} = the maximum rate of evaporization , $7x10^{23}\ r_o^3$

P = the pressure at any point along the trail

P_{max} = pressure where q_{max} occurs , $4x10^{-2}\ r_o$

and

r_o = the initial radius of the meteoric particle.

Dubin(11) applied Eq. (19) with the meteor number-size distribution due to Watson(12) to calculate the rate of vaporization of meteoric materials for 85 km, 100 km, and 115 km, and found that the maximum deposition could be expected at the lower altitudes. However, recent satellite measurements reported by McCracken et al.(13) show that the Watson distribution severely underestimated the component due to masses between 10^{-6} to 10^{-10} gms by as much as four orders of magnitude. Application of the McCracken distribution to Eq. (19) would result in raising the altitude at which maximum vaporization occurs. Accordingly, an altitude of 105 km was chosen for the present work. The corresponding altitudes (on a number density basis) for Venus and Mars are 192 km and 270 km as given in Table 1.

Concerning the absolute N_o-value, Junge et al.(3) used 3×10^4 Na atoms/cm^2 sec, but state that this value may be incorrect by two orders of magnitude. In view of this uncertainty and the lack of knowledge for the planets Venus and Mars, this parameter was carried through as an adjustable value. Accordingly, the results of the present calculations will be presented as altitude profiles of the relative number density of sodium atoms for the various cases considered. Fortunately, the N_o-value enters as a factor in the analytical solution so that the calculated number density values are directly proportional to the N_o-value selected.

b. Lower Boundary of Exosphere Sink

An exospheric sink was employed as a convenient boundary condition. However, to reflect the real case, the strength of the sink is adjusted so that essentially no significant losses occur via escape. Thus, under steady state conditions, most of the loss of sodium is due to the sink at the surface of the planet. Finally, it turns out that for altitudes above a few scale heights, the position of the lower boundary of exospheric sink has relatively little effect; it is convenient to place it at infinity.

c. Chemical Consumption Probability Per Sodium Atom

Since the calculations are sensitive to this parameter, care should be exercised in choosing the proper form and value for b(z). Fortunately, there appear to be sufficient data to make a reasonable estimate for the case of Earth. On the other hand, the required data are essentially lacking in the case of the planets Venus and Mars. In any case, since b-values are required, they were calculated on the basis of available data for the Earth; and in the case of Venus and Mars, the required data were obtained by determining the amount of photochemically produced O_2 in the upper atmospheres of Venus and Mars via the solar photodissociation of CO_2. The method will be discussed and clarified below.

(1) Chemical Consumption Probability for Planet Earth

The derivation of the b-value of Earth is relatively simple since for the altitudes of interest, the dominant process for the chemical consumption of sodium atoms is

$$Na + O_2 + M = NaO_2 + M \ ; \quad k = 5x10^{-30} cm^6/sec \ \text{(Ref. 14)} \qquad (20)$$

The appropriate curve has been derived by Marmo and shown as Fig. 2 in the original report.(8) For mathematical convenience, a simplification is achieved if the probability can be expressed by the form

$$b(z) = B_o \exp (- p_o z/H) \ .$$

It can be shown that in this case the published values can be very closely approximated at all pertinent altitudes by choosing $B_o = 4.8 \times 10^{10}$ sec^{-1}, $p_o = 2.2$, and $H = 6.6$ km. These are the values employed and are shown in Table 1.

(2) Chemical Consumption Probability for Venus and Mars

The oxygen content for the upper atmospheres of these planets is not well known so that b-values could range from zero to perhaps as high as those appropriate to Earth. In order to arrive at a somewhat realistic estimate of the strength of the chemical sinks in these planets, the photochemical processes were examined in detail and are described below.

For this study, the isothermal atmospheres were assumed to consist of only nitrogen and CO_2 in which the CO_2 contents are assumed to be 2½ percent(15) and 2 percent(16) for Venus and Mars, respectively. For Venus, the atmosphere was considered isothermal at 297°K for all altitudes above the occultation level in accord with deVaucouleurs and Menzel.(17) Since it will be shown that essentially all the important photochemistry occurs above this level, this cannot be too objectionable. The surface pressure was obtained by extrapolation and found to be 27 atm.

For Mars, the temperature of the isothermal atmosphere was taken as 220°K with a surface pressure of about 64 mm Hg.

The effective photochemical reactions include:

$$CO_2 + h\nu \rightarrow CO + O \qquad \alpha_1 \tag{21}$$

$$CO + O + M \rightarrow CO_2 + M \qquad k_1 = 5.0\times10^{-36} cc^2/molecule^2 sec \tag{22}$$

$$O_2 + h\nu \rightarrow O + O \qquad \alpha_2 \tag{23}$$

$$O + O + M \rightarrow O_2 + M \qquad k_2 = 2.7\times10^{-33} cc^2/molecule^2 sec \tag{24}$$

$$O_3 + h\nu \rightarrow O_2 + O \qquad \alpha_3 \tag{25}$$

$$O + O_2 + M \rightarrow O_3 + M \qquad k_3 = 5.0\times10^{-34} cc^2/molecule^2 sec \tag{26}$$

$$O_3 + O \rightarrow 2O_2 \qquad k_4 = 6.8\times10^{-17} cc/molecule\ sec\ . \tag{27}$$

At an altitude h,

$$\alpha_i = \sum_\lambda c_i\ I_o\ e^{-\tau}$$

where

c = total absorption cross section

τ = optical thickness = $\int_z^\infty \sum_i c_i\ n_i\ dz$

and

I_o = the solar flux incident at the top of the Venusian atmosphere.

Assuming photochemical equilibrium, the steady state concentrations of oxygen can be given by

$$n(O_2) = \frac{k_2\ n^2(O)\ n(N_2)\ \left[\alpha_3 + k_4\ n(O)\right]}{\alpha_2\alpha_3 + \alpha_2 k_4\ n(O) - k_3 k_4\ n^2(O)\ n(N_2)} \tag{28}$$

where that of atomic oxygen must be obtained from

$$n^4(O) + An^3(O) + Bn^2(O) + Cn(O) + D = 0 \tag{29}$$

where

$$A = \frac{\alpha_1 n(N_2)\left[3k_2k_3n(N_2)+2k_2k_4-k_3k_4\right]+\left[k_1n(N_2)+k_5\right]\left[\alpha_2k_4+2\alpha_3k_2n(N_2)\right]}{n(N_2)\left[k_1n(N_2)+k_5\right]\left[3k_2k_3n(N_2)+2k_2k_4-k_3k_4\right]} \tag{30}$$

$$B = \frac{\alpha_1k_4\left[\alpha_2+k_3n(N_2)n_o(CO_2)\ e^{-z/H}\right]+\alpha_3n(N_2)\left[2\alpha_1k_2+\alpha_2k_1\right] + k_5\alpha_2\alpha_3}{n(N_2)\left[k_1n(N_2)+k_5\right]\left[3k_2k_3n(N_2)+2k_2k_4-k_3k_4\right]} \tag{31}$$

$$C = \frac{\alpha_1\alpha_2\left[\alpha_3-k_4n_o(CO_2)\ e^{-z/H}\right]}{n(N_2)\left[k_1n(N_2)+k_5\right]\left[3k_2k_3n(N_2)+2k_2k_4-k_3k_4\right]} \tag{32}$$

$$D = \frac{-\ \alpha_1\alpha_2\alpha_3n_o(CO_2)\ e^{-z/H}}{n(N_2)\left[k_1n(N_2)+k_5\right]\left[3k_2k_3n(N_2)+2k_2k_4-k_3k_4\right]}\ . \tag{33}$$

Solving the quartic Equation (29) for the atomic oxygen concentration enables calculation of $n(O_2)$ by Equation (28, thus describing the O_2-particle density distribution. The appropriate calculations were performed on the 1620 IBM which yielded the results shown in Figures 2 and 3 which show the resulting photochemically-produced O_2-altitude distributions on the planets Venus and Mars, respectively. It is evident that the O_2 distributions shown in Figs. 2 and 3 cannot be readily represented by a function of the form B_o exp (-pz/H) as in the case of Earth. However, for the present model, the oxygen content of the lower atmosphere is not important,

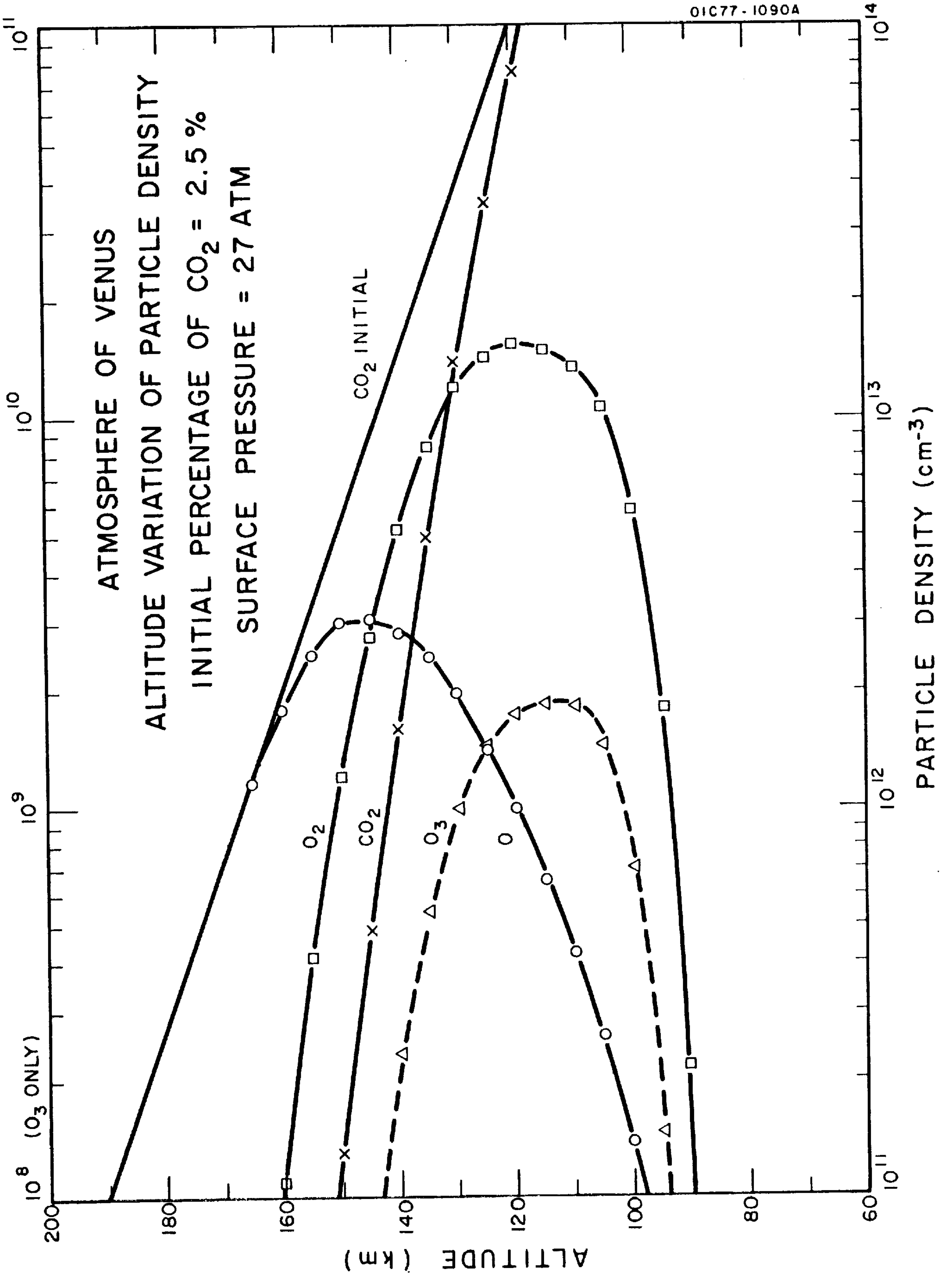

01C77-1090A
ATMOSPHERE OF VENUS
ALTITUDE VARIATION OF PARTICLE DENSITY
INITIAL PERCENTAGE OF CO_2 = 2.5 %
SURFACE PRESSURE = 27 ATM
CO_2 INITIAL
O_2
CO_2
O_3
O
(O_3 ONLY)
10^8
10^9
10^{10}
10^{11}
10^{11}
10^{12}
10^{13}
10^{14}
PARTICLE DENSITY (cm^{-3})
200
180
160
140
120
100
80
60
ALTITUDE (km)

Figure 2.

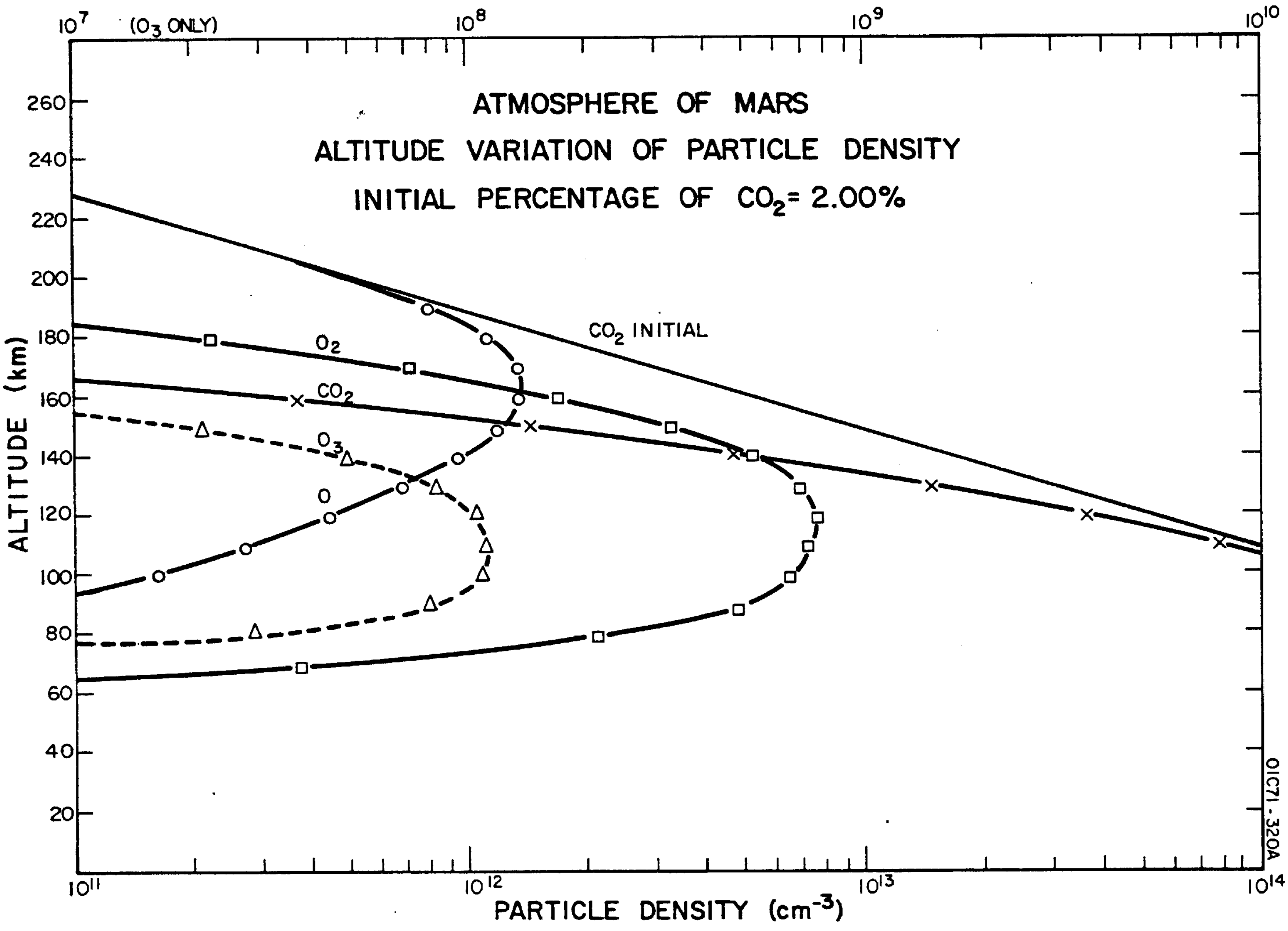
ATMOSPHERE OF MARS
ALTITUDE VARIATION OF PARTICLE DENSITY
INITIAL PERCENTAGE OF CO_2= 2.00%
10^7
(O_3 ONLY)
10^8
10^9
10^{10}
260
240
220
200
180
160
140
120
100
80
60
40
20
ALTITUDE (km)
CO_2 INITIAL
O_2
CO_2
O_3
O
10^{11}
10^{12}
10^{13}
10^{14}
PARTICLE DENSITY (cm^{-3})
01C71-320A

Figure 3.

and at least the upper altitude region of the O_2 distributions can be closely approximated by a function of the proper form when the appropriate values shown in Table 1 are employed.

IV. RESULTS AND DISCUSSION

With the values shown in Table 1, the appropriate solutions were obtained for Eqs. (17) for Cases I and II in the planets Earth, Venus and Mars. The numerical results are summarized in Figs. 4, 5, 6, 7, 8 and 9, and are discussed in that order.

Figure 4 summarizes the numerical results for Case II in the Earth's atmosphere in which the solid curve represents the results with chemical consumption, whereas the dashed curve is the result with no chemical consumption. For the present discussion, the curves can be associated on the one hand with an oxygen-rich atmosphere and on the other hand, with an atmosphere which contains no oxygen. The figure is shown to make the following points: first, it makes evident that in the Earth's atmosphere, only a minute fraction of the total sodium content is in the free atomic form; second, if the other terrestrial planets lack oxygen, the free sodium distribution curves would be expected to be similar to the dashed curve shown in Fig. 4. It can easily be shown that if, indeed, this dashed curve does prevail, the very dense ionospheres become possible and the atmospheres take on unprecedented optical characteristics. These points were previously discussed in Section II. On the other hand, it is evident that in none of the three terrestrial planetary atmospheres does this situation actually occur. Thus, if comparable meteoric fluxes are assumed for the other planets, there probably is sufficient oxygen (or other suitable contaminant) in the Venus and Mars atmospheres to preclude

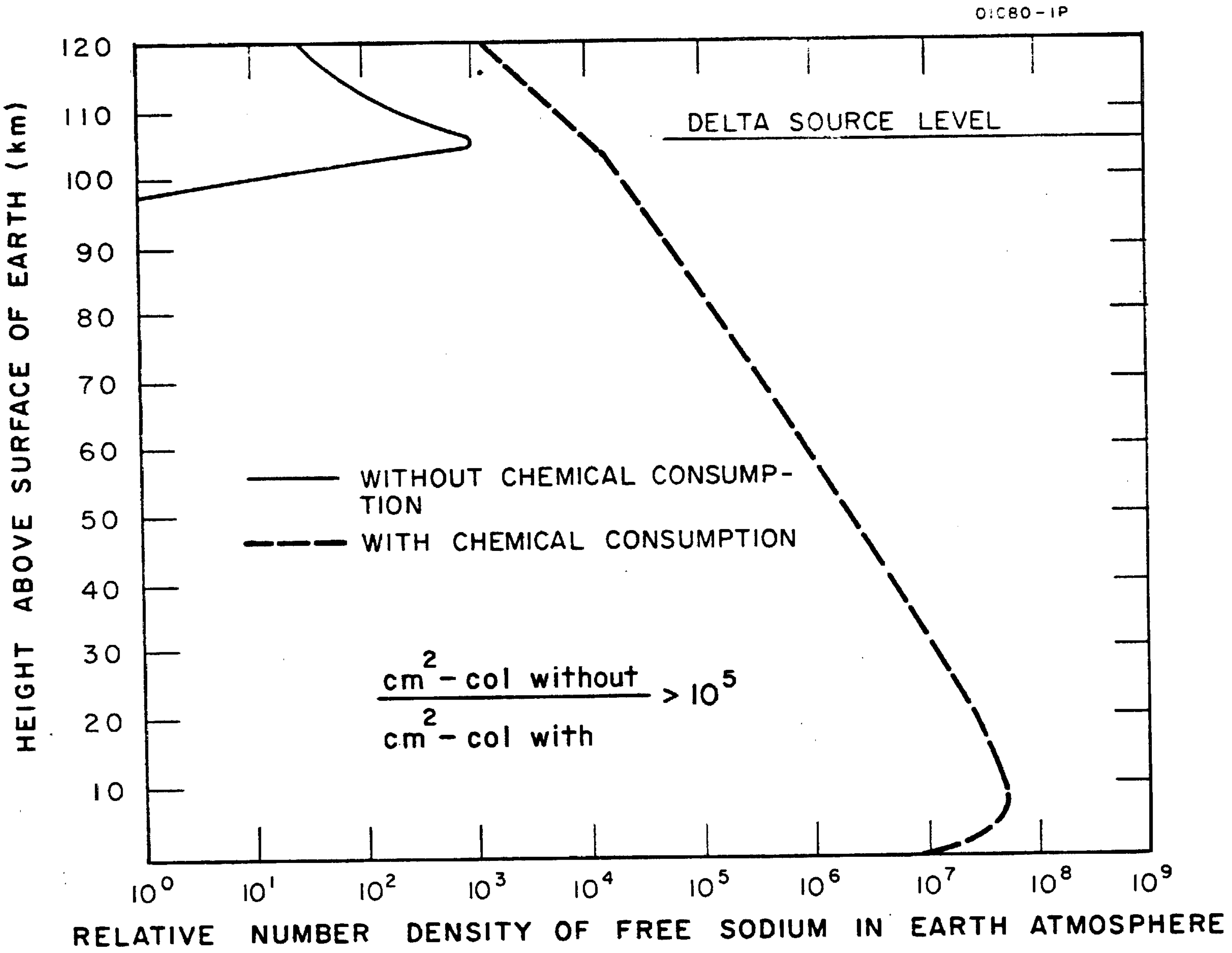

0:C80-1P
HEIGHT ABOVE SURFACE OF EARTH (km)
120
110
100
90
80
70
60
50
40
30
20
10
DELTA SOURCE LEVEL
WITHOUT CHEMICAL CONSUMPTION
WITH CHEMICAL CONSUMPTION
$\frac{cm^2 - col\ without}{cm^2 - col\ with} > 10^5$
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
RELATIVE NUMBER DENSITY OF FREE SODIUM IN EARTH ATMOSPHERE

Figure 4.

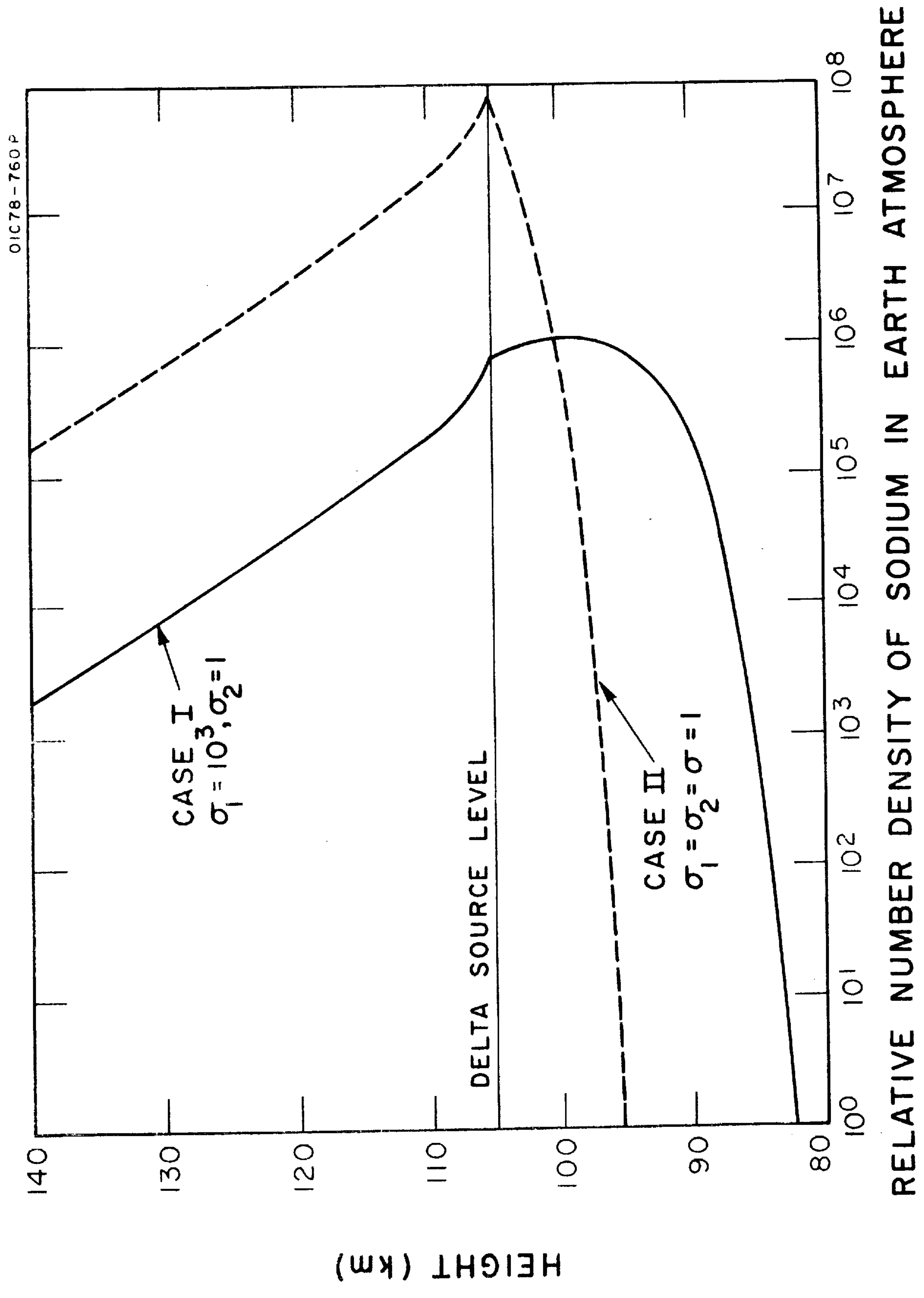

01C78-760P
HEIGHT (km)
140
130
120
110
100
90
80
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
RELATIVE NUMBER DENSITY OF SODIUM IN EARTH ATMOSPHERE
DELTA SOURCE LEVEL
CASE I
$\sigma_1 = 10^3, \sigma_2 = 1$
CASE II
$\sigma_1 = \sigma_2 = \sigma = 1$

Figure 5.

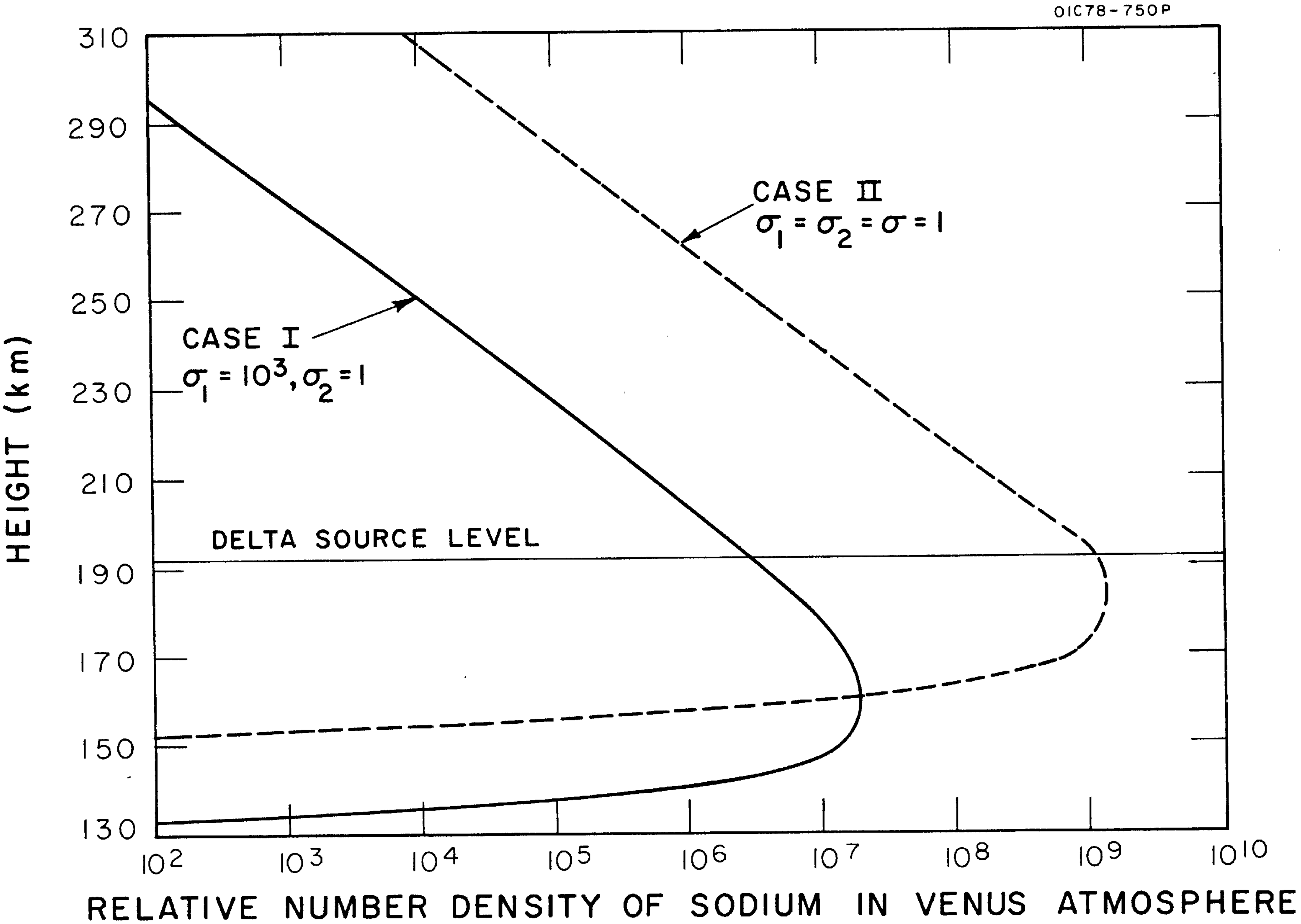

01C78-750P
HEIGHT (km)
310
290
270
250
230
210
190
170
150
130
CASE II
$\sigma_1 = \sigma_2 = \sigma = 1$
CASE I
$\sigma_1 = 10^3, \sigma_2 = 1$
DELTA SOURCE LEVEL
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
RELATIVE NUMBER DENSITY OF SODIUM IN VENUS ATMOSPHERE

Figure 6.

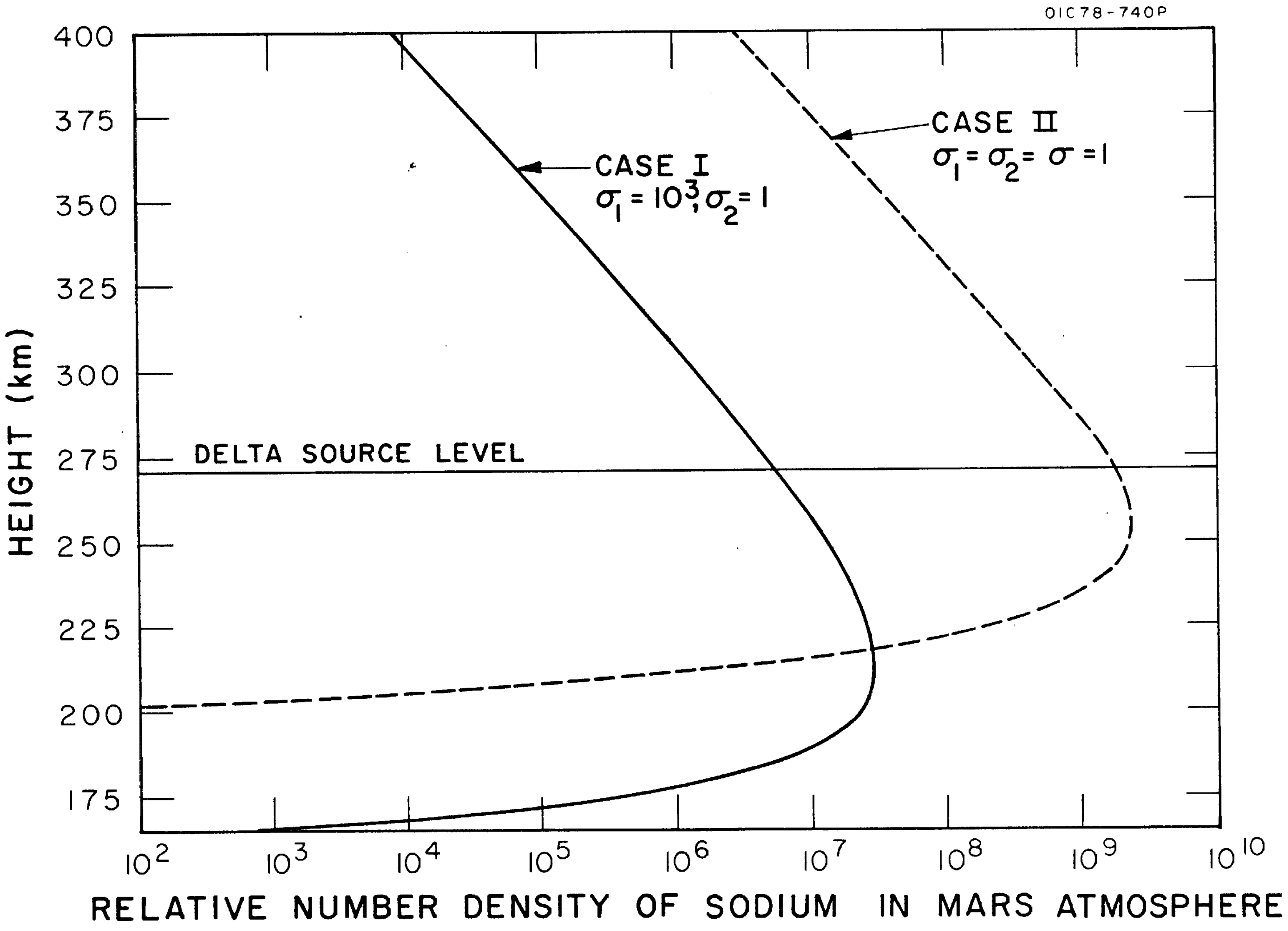
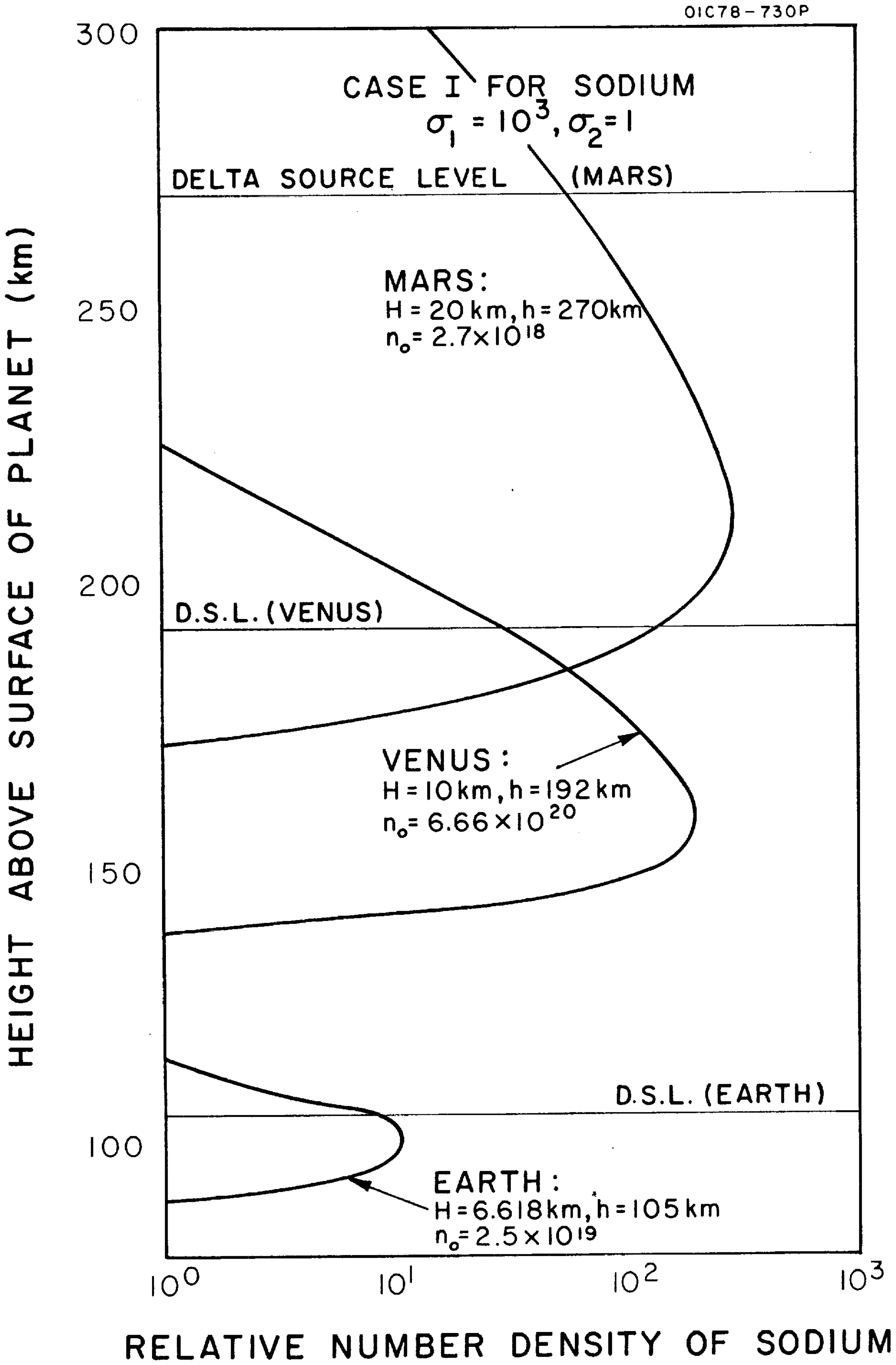

01C78-740P
HEIGHT (km)
400
375
350
325
300
275
250
225
200
175
DELTA SOURCE LEVEL
CASE I
$\sigma_1 = 10^3, \sigma_2 = 1$
CASE II
$\sigma_1 = \sigma_2 = \sigma = 1$
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
RELATIVE NUMBER DENSITY OF SODIUM IN MARS ATMOSPHERE

Figure 7.



01C78-730P
CASE I FOR SODIUM
$\sigma_1 = 10^3, \sigma_2 = 1$
DELTA SOURCE LEVEL (MARS)
MARS:
H = 20 km, h = 270 km
$n_o = 2.7 \times 10^{18}$
D.S.L. (VENUS)
VENUS:
H = 10 km, h = 192 km
$n_o = 6.66 \times 10^{20}$
D.S.L. (EARTH)
EARTH:
H = 6.618 km, h = 105 km
$n_o = 2.5 \times 10^{19}$
300
250
200
150
100
HEIGHT ABOVE SURFACE OF PLANET (km)
10^0
10^1
10^2
10^3
RELATIVE NUMBER DENSITY OF SODIUM

Figure 8.

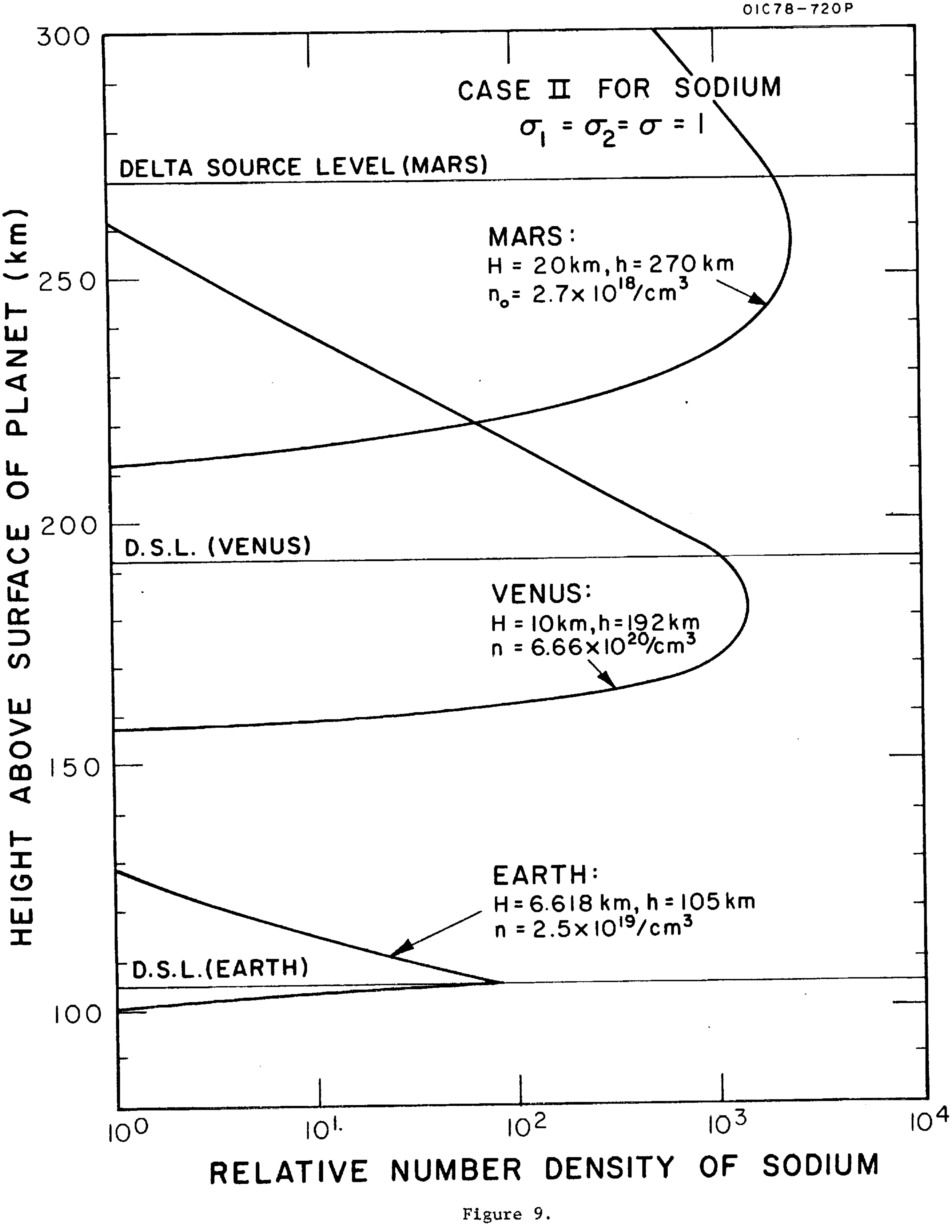

01C78-720P
CASE II FOR SODIUM
$\sigma_1 = \sigma_2 = \sigma = 1$
DELTA SOURCE LEVEL (MARS)
MARS:
H = 20 km, h = 270 km
$n_o = 2.7\times10^{18}/cm^3$
D.S.L. (VENUS)
VENUS:
H = 10 km, h = 192 km
$n = 6.66\times10^{20}/cm^3$
EARTH:
H = 6.618 km, h = 105 km
$n = 2.5\times10^{19}/cm^3$
D.S.L. (EARTH)
300
250
200
150
100
HEIGHT ABOVE SURFACE OF PLANET (km)
10^0
10^1
10^2
10^3
10^4
RELATIVE NUMBER DENSITY OF SODIUM

Figure 9.

the total conservation of free sodium. However, the role of an oxygen-poor atmosphere must still be examined, since it does not preclude that the planetary atmospheres may become optically thick in some specific spectral regions and that the meteoric debris ions may be the dominant species in the ionosphere.

In order to further investigate the possibilities discussed at the end of the previous paragraph, reference is made to Figs. 5, 6 and 7 which depict the altitude distributions of the relative number densities of sodium in the three planetary atmospheres. The solid curve represents Case I (turbulent diffusion below the delta source level), and the dotted curves represent Case II (molecular diffusion at all altitudes of interest). The three sets of curves show the effect of turbulent diffusion in lowering the entire sodium-altitude distribution curve. At the same time, this is accompanied by a corresponding decrease in the peak values for the sodium number densities. In the case of Earth, even though some pertinent data do exist, a detailed comparison of this crude model is unwarranted. This is especially true in that the subsequent effects of the solar radiation were not considered in this model. Indeed, it is quite surprising that the calculated distribution is not unlike that measured by several investigators.(1,18,19)

Perhaps the present preliminary crude results can be best employed with reference to Figs. 8 and 9. The figures can be used to make a ready comparison of Case I and Case II for the resulting relative number density of sodium in the three terrestrial planetary atmospheres. Even a cursory comparison of these curves shows that although the total O_2-contents on the planets Venus and Mars are only about 1 part in 10^5 of that of Earth, it is sufficient to establish effective chemical sinks. However, it is also evident that there is considerably more free sodium in the planets Venus and Mars than that which exists in the Earth atmosphere. In fact, it can be noted that if the values shown in the figures are normalized against a value of $5x10^9$ cm^2-column for Earth sodium, then the atmospheres of both Venus and Mars are optically thick for the sodium D-lines. This, of course, suggests that spectrographic observations be made of these planetary atmospheres in order to check the validity of this hypothesis. If an affirmative answer is obtained, this would make evident that the sea origin for Earth sodium is an unnecessary mechanism to invoke, and at the same time give critical information concerning the meteoric and micrometeoric flux. Concerning planetary ionospheres, the data in Figs. 8 and 9 are not directly applicable, since (except for the generation of photochemically-produced O_2) the model does not take account of the solar photoionizing flux or of the photodissociation of NaO_2 into free sodium and molecular oxygen. The latter process could generate a second and more dense free sodium peak in the lower atmospheres of Venus and Mars. Due to this possibility, one should not preclude the possibility of the generation of a dense (greater than 10^7 electrons cm^{-3}) ionosphere on these planets.

The more obvious improvements will be incorporated into the present model and some of the more interesting consequences of the present work will be the subject of subsequent investigations in the role of interplanetary debris in planetary atmospheres.

REFERENCES

1. Lytle, E.A. and Hunten, D.M., J. Atmos. Terr. Phys. 16, 236 (1959).

2. Sullivan, H M. and Hunten, D.M., Nature (London) (in press).

3. Junge, C.E., Oldenberg, O. and Wasson, J.T., J. Geophys. Res. 67, 1027 (1962).

4. Istomin, V.G., Doklady Akademii Nauk SSSR, 136, No. 5, 1066-1068 (1961).

5. Jones, A.V., Ann Geophys. 14, 179 (1958).

6. Dufay, M., Ann. Geophys. 14, 391 (1958).

7. Nagy, E., Fizikai szemle, No. 4, 124-127 (1962).

8. Marmo, F.F., Space Research II (North-Holland Publishing Company, Amsterdam, 1961), pp. 1159-1193.

9. Lettau, H., "Diffusion in the Upper Atmosphere," pp. 320-333 of Compendium of Meteorology, Ed. T.F. Malone, Am. Meteorological Soc., Boston, Mass. (1951).

10. Herlofson, N , Phys. Soc. Rep. Prog. Phys. 11, 444 (1948).

11. Dubin, M., "Meteors" (A Symposium on Meteor Physics): Special Supplement (Vol. 2) to J. Atmos. Terr. Phys. (1955).

12. Watson, F., Between the Planets (Blakiston, 1941), pp. 140-177.

13. McCracken, C.W., Alexander, W.M. and Dubin, M., Nature, 192, No. 4801, 441-442 (Nov 4, 1961).

14. Bawn, C.E.H. and Evans, A.G., Trans. Faraday Soc. 33, 1571, 1580 (1937).

15. Spinrad, H., Pub A.S.P 74, 187 (June 1962).

16. Marmo, F.F. and Warneck, P., GCA Technical Report No. 61-20-N, Final Report Contract No. NASw-395 (December 1961).

17. DeVaucouleurs, G. and Menzel, D.H., Harvard College Obs. Sci. Report No. 3 (July 1959) Reprinted from Nature, 188, 28 (1960).

18. Tinsley, B.A. and Jones, A.V., J. Atmos. Terr. Phys. 24, 345 (1962).

19. Donahue, T.M. and Blamont, J.E., Ann. Geophys. 17, 116 (1961).