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HYDROGEN AND HELIUM IONS*

BY

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ABSTRACT

The present state of knowledge concerning the two lightest atmospheric ions (H^+ and He^+) is discussed from the viewpoint of theory and observation. Chemical processes leading to the formation and destruction of these ions, i.e., photoionization and charge transfer, as well as the diffusion process are the controlling factors for the distributions of H^+ and He^+. The experimental observations of H^+ and He^+ have been obtained by means of ion mass spectrometers aboard spacecraft, ground-based incoherent backscatter radar, as well as from VLF phenomena observed on satellites. These observations show that He^+ ions do not become a predominant ion at low solar activity, whereas at solar maximum they may play a significant role. Hydrogen ions assume their greatest importance at solar minimum when they are the predominant ion at altitudes even less than 1000 km. There is also a latitude gradient in the relative abundance of these light ions, indicating a "lack" of He^+ and H^+ at high latitudes.

1. INTRODUCTION

The fact that hydrogen ions (protons) would become the primary ionic constituent in the outermost part of the terrestrial atmosphere has been accepted for a long time. The origin and the distribution of the protons in the "protonosphere" has been the subject of some discussion [1,2], particularly in connection with whistler observations. However, the suggestion that helium ions may become an important constituent has been made only in 1961 by Nicolet [3] on the basis of satellite drag observations which could best be accounted for by assuming the presence of neutral helium in the upper atmosphere. Within a year

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of this suggestion, the presence of helium ions was verified from the altitude behavior of the total ion density distribution at high altitudes [4], as well as by direct measurements onboard the Explorer VIII satellite [5]. Since then, measurements of the light ionic constituents have been made by means of rockets and satellites, as well as by the ground-based incoherent backscatter radar technique. Unfortunately, even now, there is still relatively little experimental information available to form a thorough understanding of the altitude, latitude and time behavior of the two ionic constituents H^+ and He^+.

In the following, the present state of knowledge concerning these two ion species will be discussed from the viewpoint of both, theory and experiment. Because of the lack of sufficient observations the evolving picture will be rather sketchy, with emphasis on the established facts, which are few in number.

2. FACTORS CONTROLLING THE DISTRIBUTION OF H^+ AND He^+

The behavior of any ionic constituent X^+ is governed by the continuity equation

$$\frac{\partial n(X^+)}{\partial t} = q(X^+) - L(X^+) - \operatorname{div}\{F(X^+)\} \tag{1}$$

where q is the rate of production, L is the rate of loss due to chemical processes and div $F = n(X^+) v_D$, (with v_D the diffusion velocity) represents a local source or sink as the result of mass transport. As a first order approximation, the steady-state $(\partial n(X^+)/\partial t = 0)$ is usually considered.

There are two limiting cases, or asymptotic solutions to the steady-state continuity equation:

a. Chemical equilibrium: $q = L$

b. Diffusive equilibrium: $\operatorname{div}\{F(X^+)\} \approx \partial F/\partial z = 0$ $(v_D = 0)$

The applicability of these limiting cases depends on the appropriate time constants.

The chemical time constant is given by

$$\tau_c = \frac{n(X^+)}{q(X^+)} = \frac{n(X^+)}{L(X^+)} \tag{2}$$

where $n(X^+)$ is the concentration of the ionic constituent X^+, $q(X^+)$ is its rate of production and $L(X^+)$ is its rate of loss. The diffusion time constant is given by

$$\tau_D \approx \frac{H^2}{D(X^+)} \tag{3}$$

where H is a scale height representing the ionic constituent X^+ and D is the diffusion coefficient, which depends inversely on the collision frequency ν.

Since at higher altitudes $q(X^+)$ and $L(X^+)$ are, generally, decreasing functions of height, τ_c will increase with altitude, whereas τ_D which depends directly on the collision frequency will decrease with altitude, so that at a certain level $\tau_D = \tau_c$. Below this level we may use a chemical equilibrium distribution and above this level a diffusive equilibrium distribution as a first approximation. It should be noted, that for a detailed study one has to consider the steady state continuity equation, or even the time-dependent continuity equation if the explicit time variation is less than τ_c or τ_D [6, 7]; however, chemical equilibrium or diffusive equilibrium represent asymptotic solutions of the continuity equation. Since minor ions, such as He^+ and H^+ must diffuse through a mixture of neutral particles and the major ion 0^+, the collision frequency with the latter (because of the greater cross-section of Coulomb collisions) will be the one governing τ_D. Because of this fact, as well as the larger scale height for light ionic constituents, it can easily be visualized that a given value of τ_D will be reached at a higher altitude for a light minor ion such as He^+ or H^+ than for the major ion 0^+ which diffuses through its neutral parent gas. In fact, for 0^+ the condition $\tau_D \approx \tau_c$ occurs roughly at 300 km and represents the empirical criterion for the height of the F_2 peak given by Rishbeth and Barron [8]. The fact that 0^+ presents a "barrier" to the diffusion of H^+ as a consequence of "Coulomb diffusion" was first brought out in the work by Hanson and Ortenburger [9]. The exact altitude were $\tau_D = \tau_c$, for each ionic species, obviously depends on the number density of the constituent, temperature, rate coefficients, and diffusion coefficients. Figure 1 illustrates the temperature dependence of this altitude for H^+ and He^+, in the latter case for parametric values of the ion rate coefficient, and assuming a model distribution of 0^+.

3. CHEMICAL EQUILIBRIUM DISTRIBUTION FOR H^+ AND He^+

Although photoionization of neutral hydrogen contributes somewhat to the tal proton content [10] it is not the main source of protons. Because of the gh cross section (10^{-16} to $10^{-15} cm^2$) for the accidental resonance charge ansfer reaction [11]

$$H + 0^+ \rightleftarrows H^+ + 0 \tag{4}$$

which occurs essentially equally fast in either direction, this chemical reaction represents the source and sink for hydrogen ions. The reaction rate for (4) has been deduced to be $k_4 = 4 \times 10^{-10} cm^3 sec^{-1}$ at ionospheric temperatures [12]. The possible importance of this reaction was first suggested by Dungey [13]. Johnson [1] was the first to argue that the hydrogen ions constituting the "protonosphere" originate from this reaction. Since reaction (4) acts both as a production and loss process for H^+, the chemical equilibrium distribution for protons is given by

$$n(H^+) = \frac{9}{8} \frac{n(H)n(O^+)}{n(O)} \tag{5}$$

where 9/8 represents the ratio of the product of statistical weights for the two processes of reaction (4). Assuming the atmospheric constituents H and O to be distributed exponentially and O^+ to be the predominant ion, eq. (5) leads to

$$n(H^+) \propto \exp(z'/H(7)) \tag{6}$$

where H(7) is the scale height with an <u>effective</u> mass of 7 AMU and z' is the geopotential altitude. This means, that H^+ in chemical equilibrium is <u>increasing</u> with altitude.

Helium ions are produced by photoionization of neutral helium and lost by charge transfer reactions with molecular atmospheric constituents, since radiative recombination is too slow a process for the removal of He^+. According to recent laboratory experiments [14, 15] the most important loss processes for He^+ are the dissociative charge transfer reactions

$$He^+ + N_2 \rightarrow He + N^+ + N \tag{7}$$

$$He^+ + O_2 \rightarrow He + O^+ + O \tag{8}$$
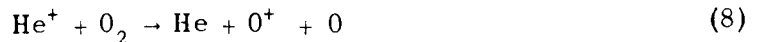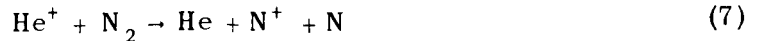
having rate coefficients k_7 and k_8.

The chemical equilibrium distribution for He^+ is therefore given by

$$n(He^+) = \frac{I_{He} \, n(He)}{k_7 \, n(N_2) + k_8 \, n(O_2)} \tag{9}$$

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where $I_{He} = 3 \times 10^{-8} sec^{-1}$ is the ionization rate coefficient for He. If $k_7 = k_8$, then because of the greater abundance of N_2, He^+ will be lost primarily by reaction (7) and only if $k_8 > k_7 n(N_2)/n(O_2)$ will reaction (8) involving O_2 be the predominant loss process.

The chemical equilibrium distribution for He^+ is thus given by

$$n(He^+) \propto exp \{z'/H(24)\} \qquad (10)$$

if He^+ is primarily lost by reaction (7), and by

$$n(He^+) \propto exp \{z'/H(28)\} \qquad (11)$$

if He^+ is lost by reaction involving O_2.

In either case, He^+ in chemical equilibrium is <u>increasing</u> with altitude. Laboratory measurements [14, 15] of the reaction rates for (7) and (8) indicate that $k_7 \approx k_8 \approx 10^{-9} cm^3 sec^{-1}$ at ionospheric temperatures and because of the equality of the rate coefficients, the loss process involving N_2 would be the controlling one. (The reaction (7) may also represent an important source of N at altitudes above 300 km.) The predominance of this process, however leads to a serious problem, since a loss rate involving N_2, having a rate coefficient $k_7 = 10^{-9} cm^3 sec^{-1}$ is not compatible with observed He^+ concentrations. In fact, from atmospheric data, a rate coefficient of $k_7 \approx 10^{-11} cm^3 sec^{-1}$ represents an upper limit. There is however the possibility that the laboratory rate coefficient is <u>not applicable</u> to the ionosphere, otherwise our ideas about the formation of He^+ ions would have to be revised drastically.

4. DIFFUSIVE EQUILIBRIUM OF H^+ AND He^+

Diffusive equilibrium is represented by the trivial solution of $\partial F/\partial z = 0$, i.e., diffusion velocity $v_D = 0$. In this case the distribution of an ionic species X^+ in an ion mixture, having a mean ionic mass $m_+ = \Sigma n(X^+)m(X^+)/\Sigma n(X^+)$ can easily be derived [16] to give

$$n(X^+) = n_0(X^+) exp - \left\{ \int_0^{z'} \left[\left(m(X^+) - \frac{T_e}{T_e + T_i} m_+ \right) \frac{g_0}{kT_i} + \frac{\partial(T_e + T_i)/\partial z'}{T_e + T_i} \right] dz' \right\} \quad (12)$$

Assuming, $T_e = T_i$, the distribution of the light ions He^+ and H^+, as long as they remain minor ions (i.e., $n(O^+) >> n(He^+)$, $n(H^+)$), is given for H^+, by

$$n(H^+) \propto \exp \{z' /H(7)\}, \qquad (13)$$

i.e., the same distribution as its chemical equilibrium distribution, and for He^+, by

$$n(He^+) \propto \exp \{z' /H(4)\} \qquad (14)$$

When either of these ions becomes the predominant ion, then

$$n(H^+) \propto \exp \{-z' /H(\tfrac{1}{2})\} \qquad (15)$$

and

$$n(He^+) \propto \exp \{- z' /H(2)\} \qquad (16)$$

The behavior of these idealized conditions of chemical and diffusive equilibrium is illustrated in Figure 2. Figure 3 shows the modification of diffusive equilibrium distributions by a gradient of the charged particle temperatures. It is obvious that in this case the concentration of the heavier ionic constituents decreases much less rapidly, in fact the He^+ and H^+ distributions are almost parallel at high altitudes. Actual observations of the altitude distribution of the two light ions H^+ and He^+ are shown in the following figures (4,5). Although the observed altitude behavior resembles somewhat the idealized diffusive equilibrium distributions the actual situation is obviously more complex. Hanson and collaborators [6, 12] have shown that the distribution can be greatly affected even in the steady state by presence of upward or downward fluxes which may distort the diffusive equilibrium distribution. In the case of He^+, the appropriate model would possibly even have to account for the time dependent term in the continuity equation (1), since the time constants for production and loss are of the order of a day [7].

5. OBSERVATIONS OF THE ALTITUDE DISTRIBUTION OF H^+ AND He^+

Actual altitude distributions of the light ions have been obtained by means of rocket-borne mass spectrometer [16, 17, 18] and by the ground based incoherent backscatter radar technique [19, 20, 21]. Some of these observations [16] refer to a situation where both ions remain a minor ion throughout the altitude

range of observations; this is true for all helium ion observations shown in Figure 6. Figure 7 shows the observed H^+ distribution and in this case virtually all incoherent backscatter observations include the altitude region where H^+ is the predominant ion (indicated by arrows). All observations shown in Figure 6 and 7 indicate that the maximum of the He^+ or H^+ concentration occurs between 500 and 600 km and that the proton concentration shows a much greater variability (from 10^3 to about $5 \times 10^4 cm^{-3}$), than He^+ whose maximum concentration is of the order of 5×10^3 to $10^4 cm^{-3}$. However, there also appear to be times when He^+ ions are not observed at all, or when their concentration must be extremely low. This behavior will be discussed in the following section.

6. TIME VARIATIONS OF THE H^+ AND He^+ CONCENTRATION

6.1 Diurnal Variation

The only complete diurnal variation of the light ion (He^+, H^+) abundance available at the present time has been obtained by means of the incoherent backscatter radar technique by Carlson and Gordon [21] at Arecibo, Puerto Rico. It refers to solar minimum condition. Figure 7 shows the relative abundance of H^+, He^+ and 0^+ throughout a winter day. According to this data, He^+ never becomes a predominant ion, in fact its highest abundance occurs during the night at about 500 km altitude when it represents ~20% of the total ion concentration; H^+ becomes the predominant ion at about 700 km during the night, and at higher altitudes during the day. This is also in good agreement with a nighttime NRL observation by means of a rocketborne ion-mass spectrometer [18], as well as with other indirect evidence for the predominance of H^+ at altitudes above 600 km during nighttime at low solar activity [24].

6.2 Long Term Variations

Observation of He^+ concentration, or rather the equal concentration levels $He^+/0^+ = 1$ and $He^+/H^+ = 1$, were made by Explorer VIII [5], the Ariel satellite [25], as well as on the Russian Cosmos 2 satellite [25]. It appears that He^+ may be a predominant ion during high solar activity, while at solar minimum protons appear to become the predominant ions, without any intervening altitude region where He^+ ions predominate. This solar cycle dependence, or rather temperature dependence, has been suggested by Bauer [27] and most of the observations available, are in qualitative agreement with such a concept. Recently, a detailed review of the long term variation of the ionic constituents 0^+, He^+ and H^+ has been made based on available satellite data by Rush and Venkatesawaran [28] whose model indicates that even at low solar activity a region where He^+ is the predominant ion exists. However, this does not seem to be borne out by any

of the directly measured altitude distributions by means of rockets and incoherent backscatter radar. A qualitative picture representing the view of this author of the long term behavior of the light ion abundance is shown in Figure 8 where the shaded regions indicate uncertainties in theory and observations. The fact that the total helium ion abundance will be smaller at low solar activity than at solar maximum has also been discussed by McElroy [29] who finds that at solar minimum, the helium ion concentration may change significantly from day to night because of an equilibrium time of about 7 hrs., leading to low concentrations, especially at night, whereas at solar maximum, because of an equilibrium time of the order of 40 hrs., no significant diurnal variation would be expected. The importance of protons at solar minimum when the escape of neutral hydrogen is reduced has been discussed in detail by Kockarts and Nicolet [30].

7. LATITUDE VARIATION OF H^+ AND He^+

The variation of abundance of light ions with latitude, specifically with magnetic latitude, has first been observed on the Ariel satellite [25], indicating that at a given altitude the concentration of He^+ and H^+ is greater at lower than at high latitudes. This has also been shown indirectly from topside sounder results which indicate a latitude gradient in the mean ionic mass, with smaller mass number at low than at high latitudes [21], as well as from direct measurements on Explorer XXII [31]. Direct evidence for a strong latitude dependence of the abundance of light ions, especially H^+ (since He^+ could not yet be detected by this technique) has been observed from the cut-off of VLF noise on the Alouette satellite [32] as well as by observations of proton whistler on the Injun satellite [33]. These results are shown in Figures 10 and 11. There is also strong evidence for a rather rapid decrease in the light ion abundance at high magnetic latitudes. It is tempting to speculate that He^+ and H^+ ions may be "drained off" from polar regions into the tail of the magnetosphere. Since the field lines issuing from polar regions are dragged back into the tail by the solar wind, ions having sufficient kinetic energy to escape the gravitational potential of the earth would travel great distances into the tail and one could, therefore, expect an accumulation of H^+ and He^+ on the nightside, compared to the dayside magnetosphere at great distances, say >8 to 10 R_e. The ions obviously can be considered "escaping" (only about 2 eV is required for He^+ and about 0.5 eV for H^+) and the concept of an ion-exosphere (since the electron temperature and therefore the ion temperature appears to be as high as a few eV at ~6 R_e [34] may apply in the tail of the magnetosphere. Recent measurements of ion composition on EGO I [35] have revealed the presence of He^+ in addition to H^+ out to distances of several earth radii. The virtually constant ratio of H^+/He^+ out to great distances may possibly be explained as the result of positive gradient in the charged particle temperatures (cf. Figure 3 of this paper). Unfortunately, however, these

measurements do not extend far enough to establish this difference between day and nightside magnetosphere at great distances. The escaping helium ions, could also contribute to the helium escape problem, since thermal escape of neutral helium is insufficient to explain the loss of helium from the terrestrial atmosphere.

8. CONCLUSION

It is now generally accepted that the source and sink for H^+ is the charge transfer reaction $H + O^+ \rightleftarrows H^+ + O$, while helium ions are produced by photoionization and lost by charge transfer processes involving the molecular constituents, O_2 and N_2. There is, however, presently a serious discrepancy between values of the rate coefficient for the helium ion loss process as measured in laboratory experiments and those inferred from atmospheric observations which needs to be resolved. The observed H^+ and He^+ distributions, do not follow simple equilibrium distributions, but may be interpreted as the result of the combined effects of chemical processes and diffusion. Observations indicate that He^+ may become a predominant ion over a limited altitude range during solar maximum, but may be of relatively little importance at solar minimum, when protons become the predominant ionic constituent at altitudes above 600 km. The relative abundance of the light ions exhibits a temperature dependence for which qualitative models can be derived. In addition, there is also a pronounced latitude dependence of H^+ and He^+, with a "lack" of the light ions at high latitudes and an abundance in the equatorial region, indicating a geomagnetic control of the light ion abundance.

With the current availability of a number of techniques for observing the concentrations of H^+ ahd He^+ from rockets and satellites, as well as from the ground, the experimental data which will be accumulated over the next few years will hopefully provide a better understanding of the physical processes responsible for the altitude, latitude and time behavior of the light ions H^+ and He^+.

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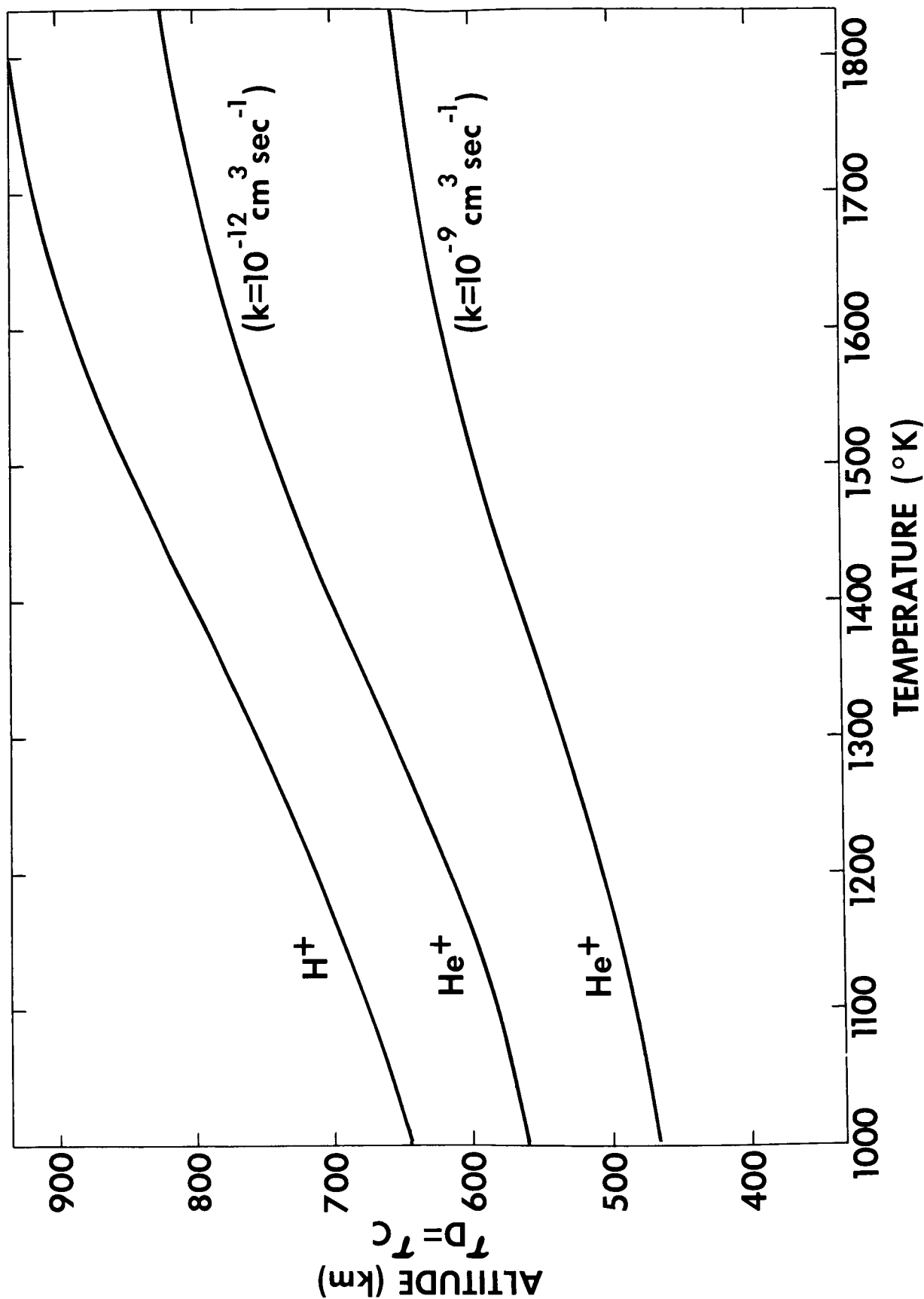
Figure 1—Altitude where chemical and diffusion time constants become equal for He+ and H+ as a function of temperature. Below this altitude chemical processes are the controlling factors for the ion distribution while above this altitude the distribution is controlled by diffusion. (For He+, two different chemical loss rate coefficients k are used.)
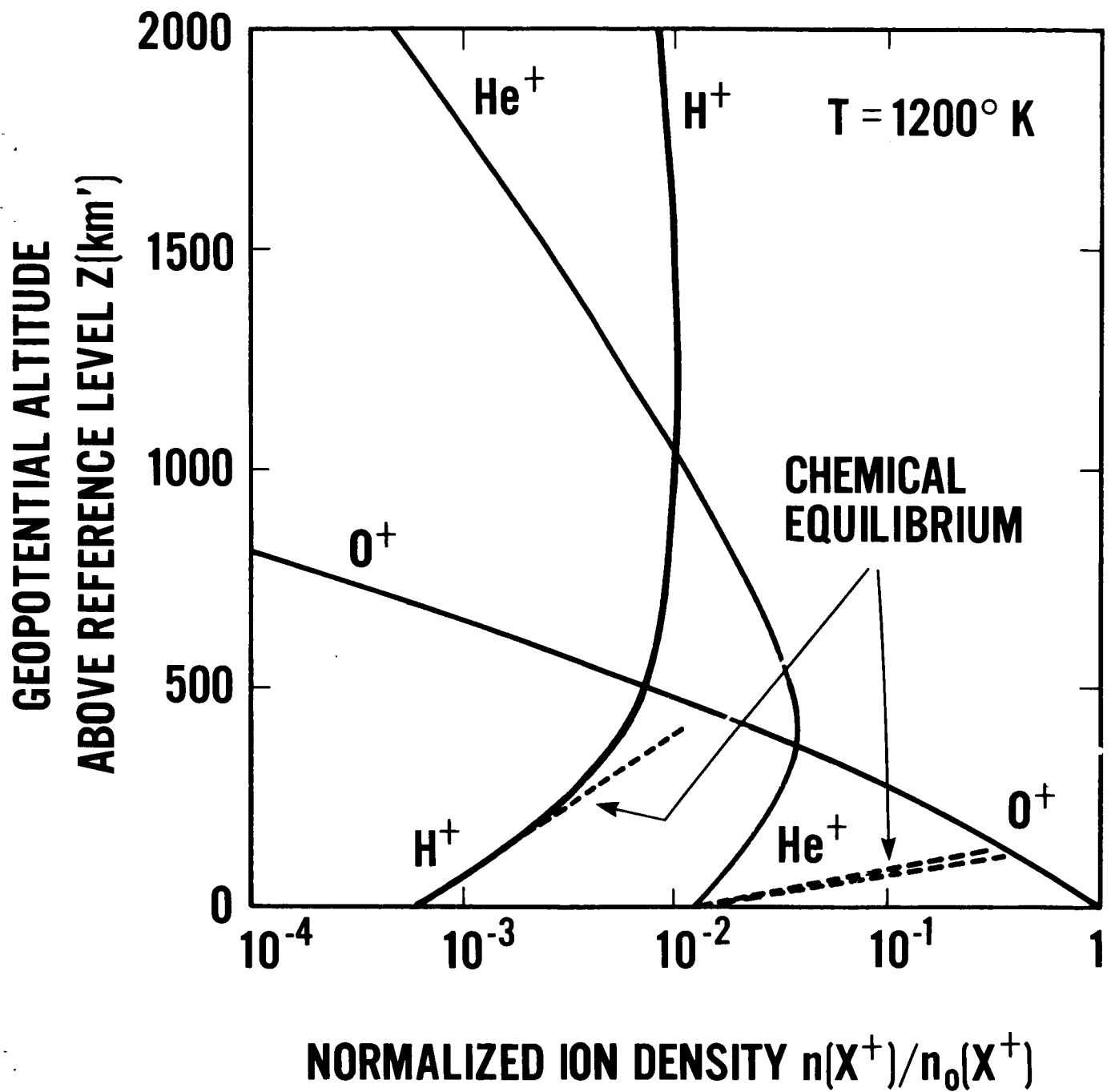
Figure 2—Chemical and diffusive equilibrium distributions for H^+, He^+ in the presence of O^+ for isothermal conditions with $T_e = T_i = T = 1200°K$
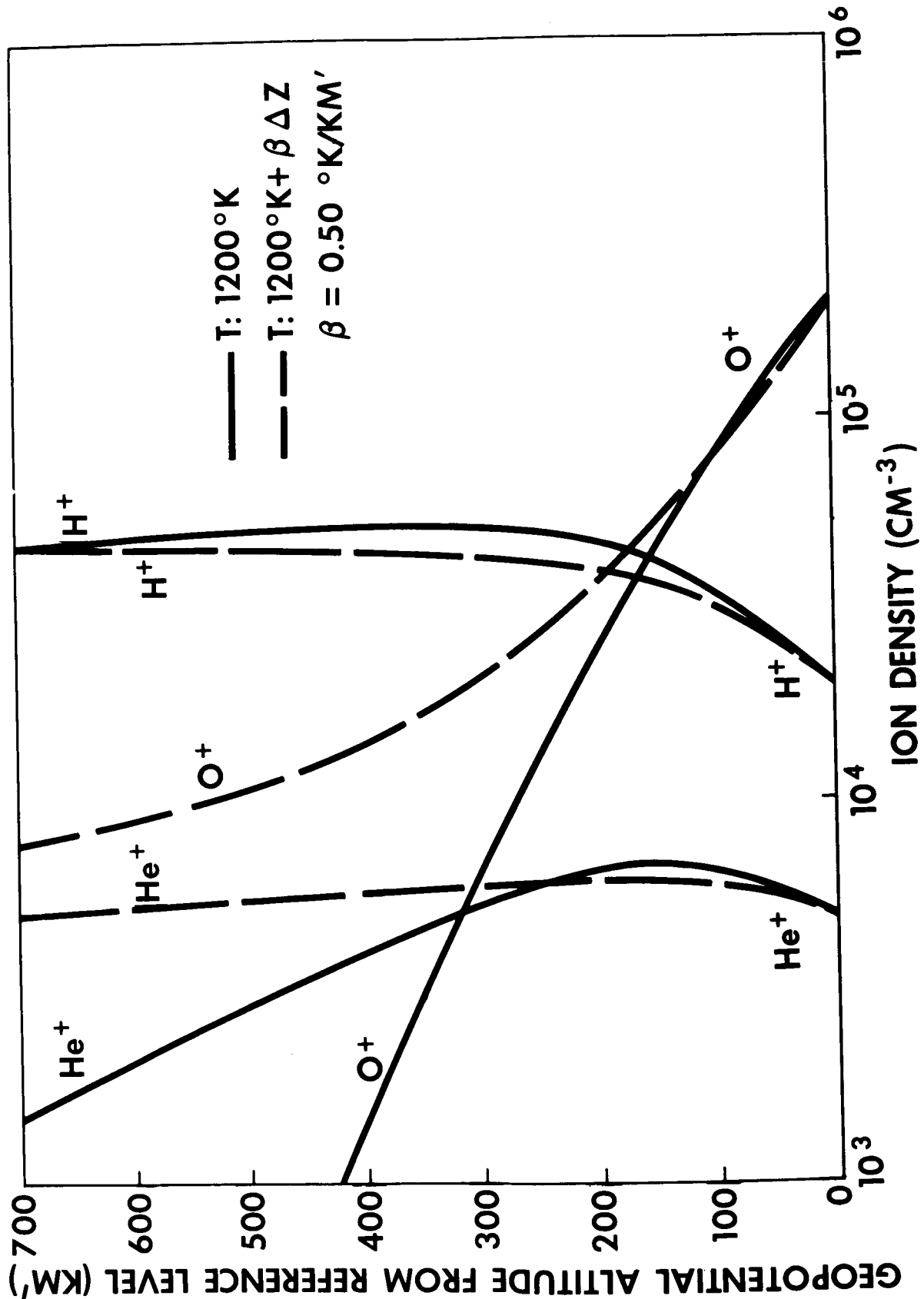
Figure 3–The effect of a positive gradient in the charged particle temperatures on the diffusive equilibrium distribution of H⁺, He⁺ and O⁺ is shown by comparison with the isothermal case
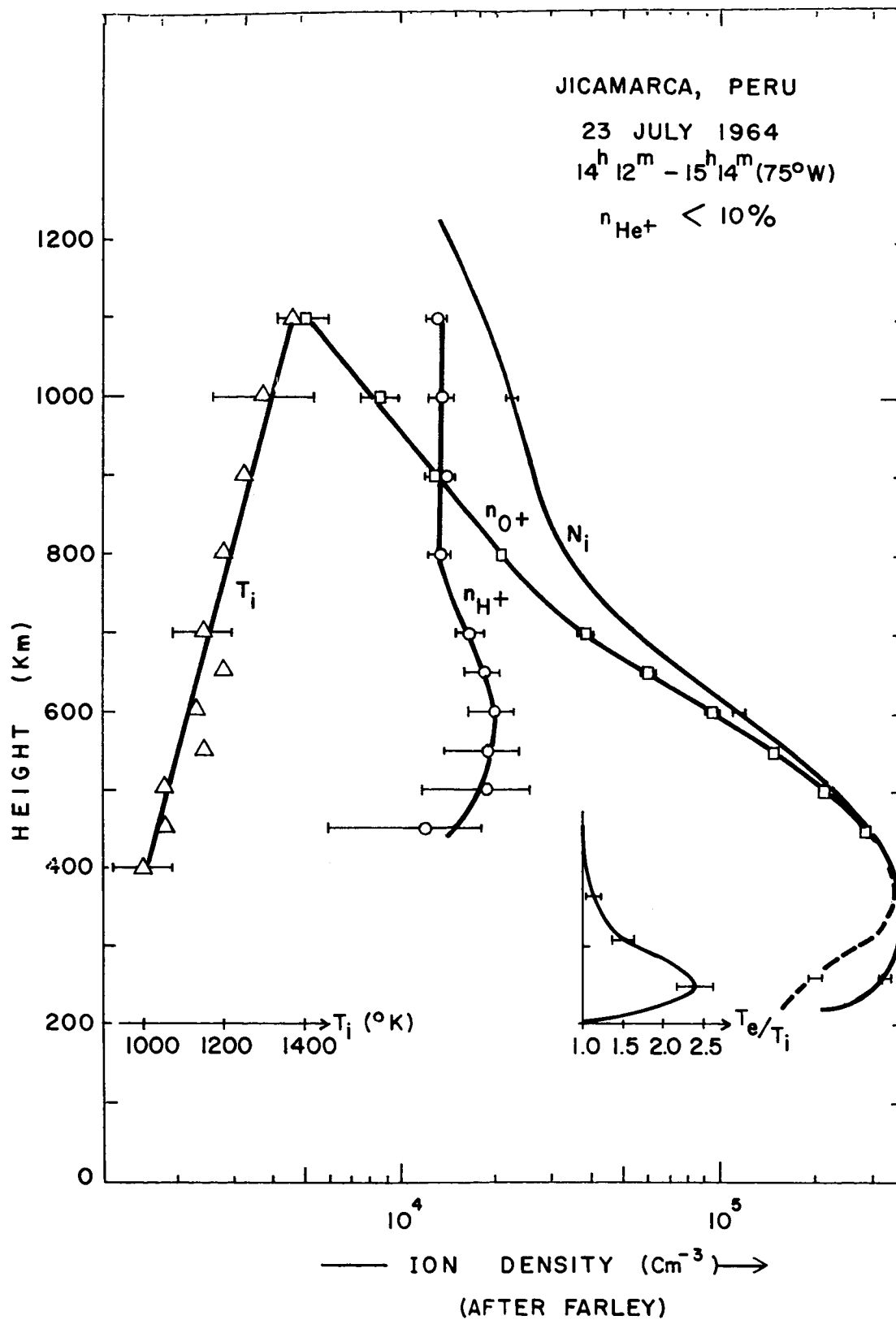
Figure 4—Altitude profile of H+ and O+ obtained by means of the incoherent radar back-scatter technique (after Farley [20]).
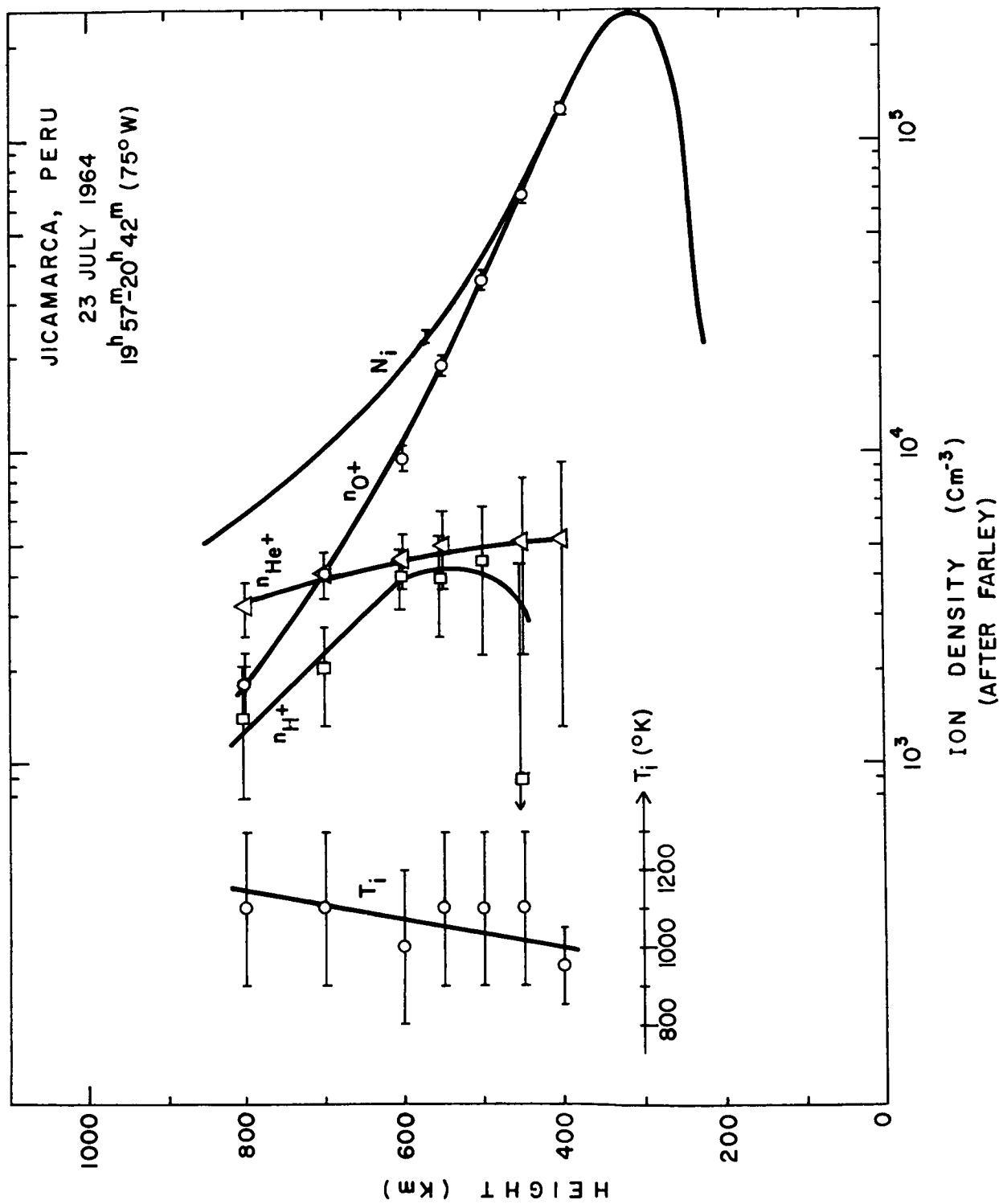
Figure 5–Altitude distribution of H+, He+ and 0+ obtained by the incoherent radar backscatter technique (after Farley [20])

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OBSERVED
He⁺ DISTRIBUTIONS

① TAYLOR et al
OCT 10, 1961 1240 LMT

② POKHUNKOV
NOV 15, 1961 1600 LMT

③ FARLEY
JULY 23, 1964 1957 LMT
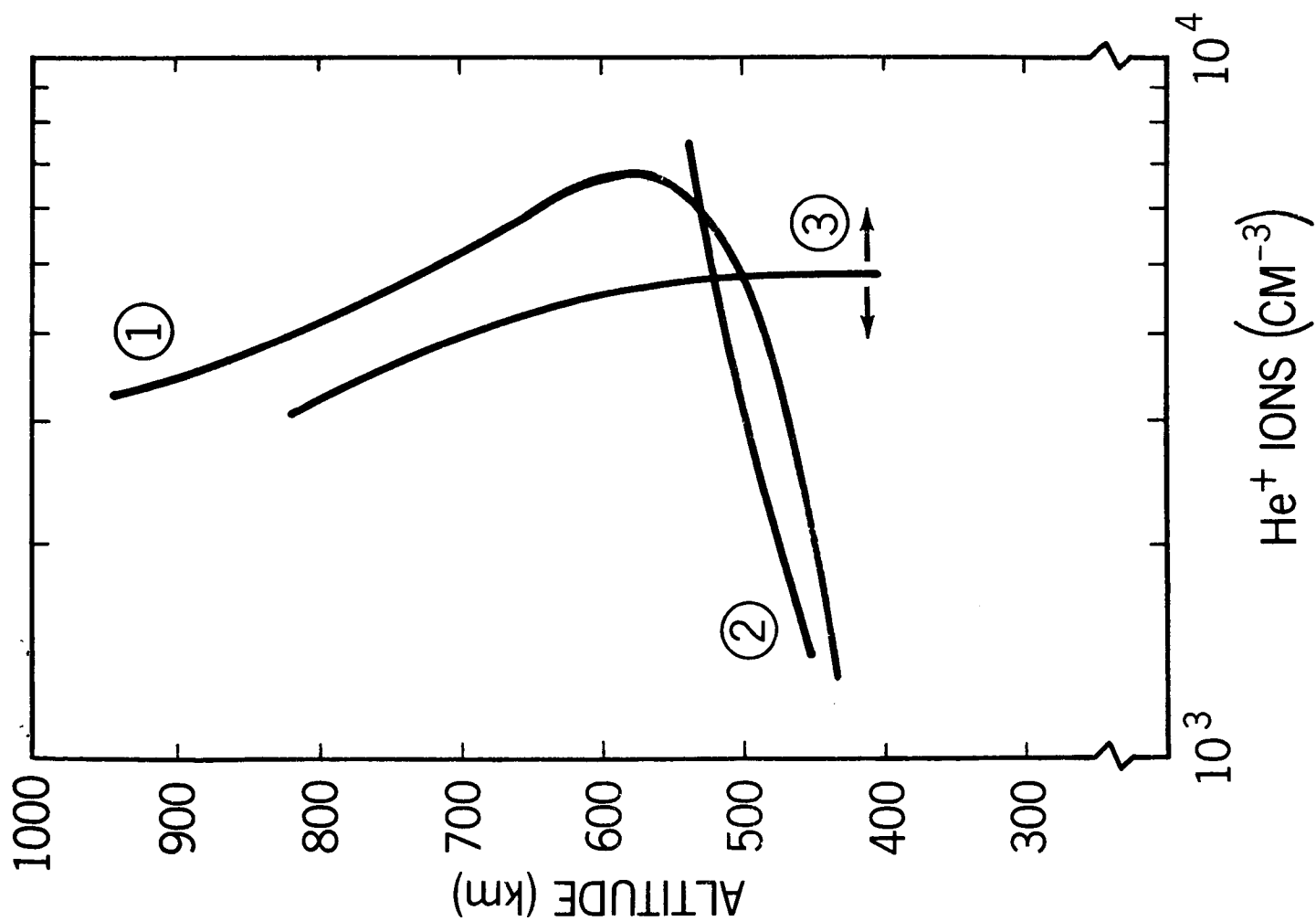
Figure 6—Observed altitude distributions of He⁺
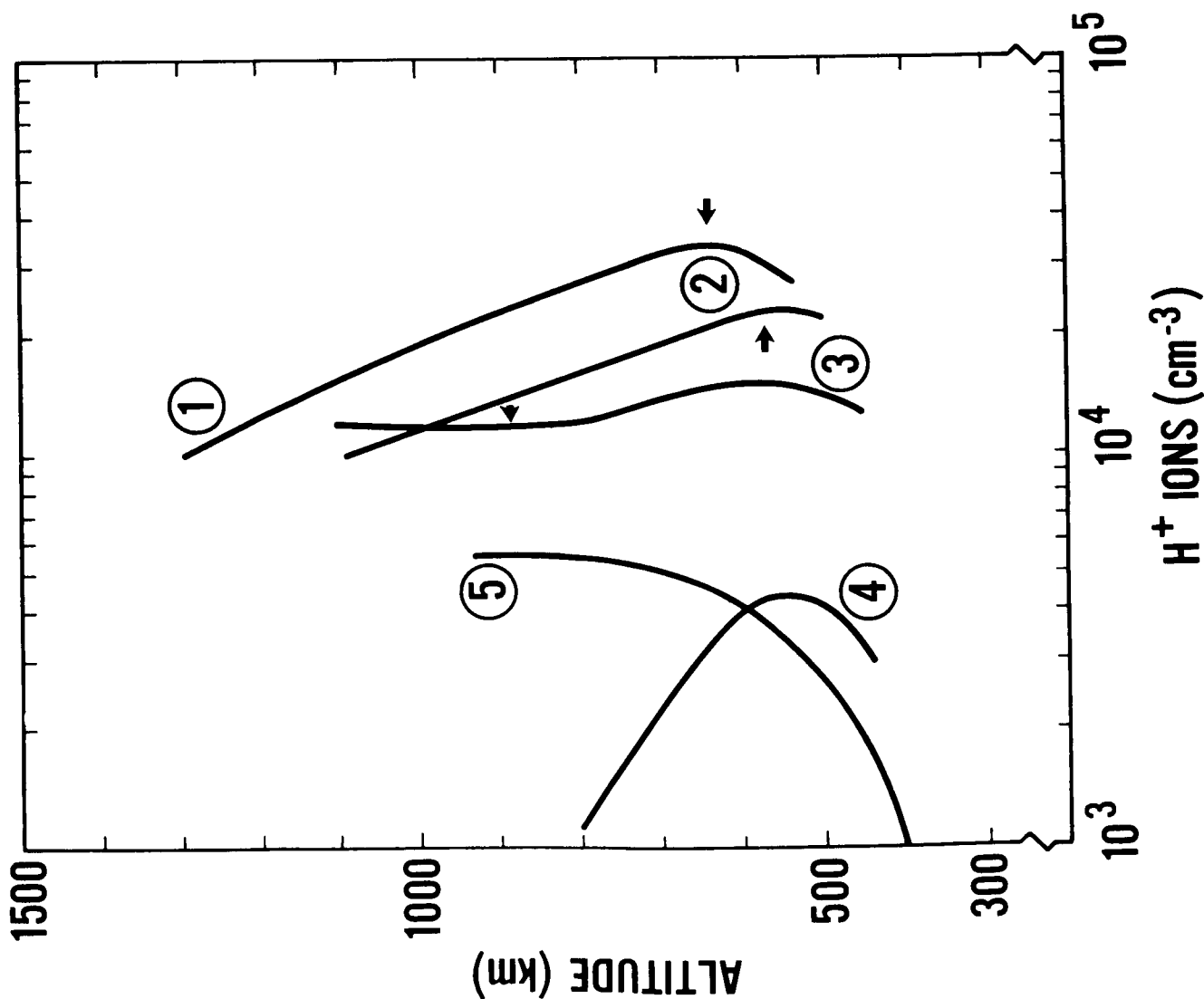
Figure 7—Observed altitude distributions of H⁺. (Arrows indicate altitude above which H⁺ becomes the predominant ion.)
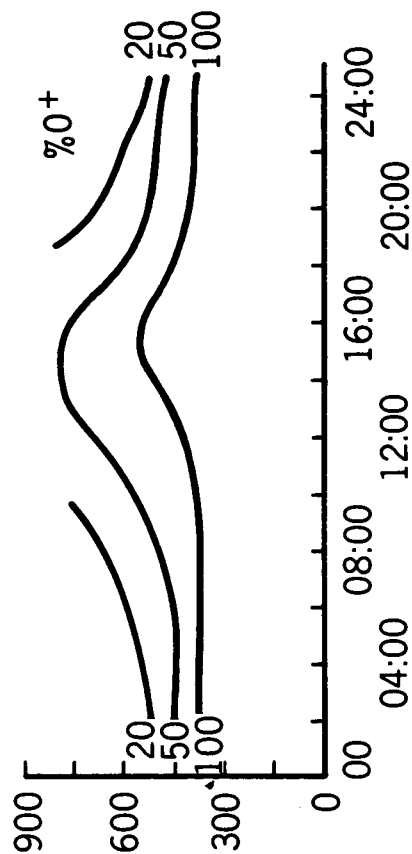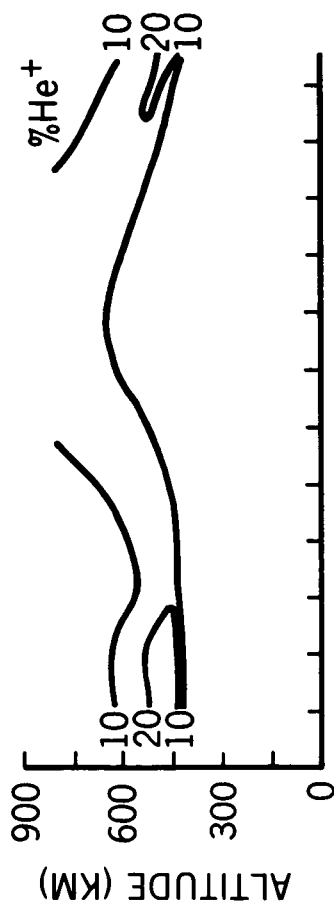
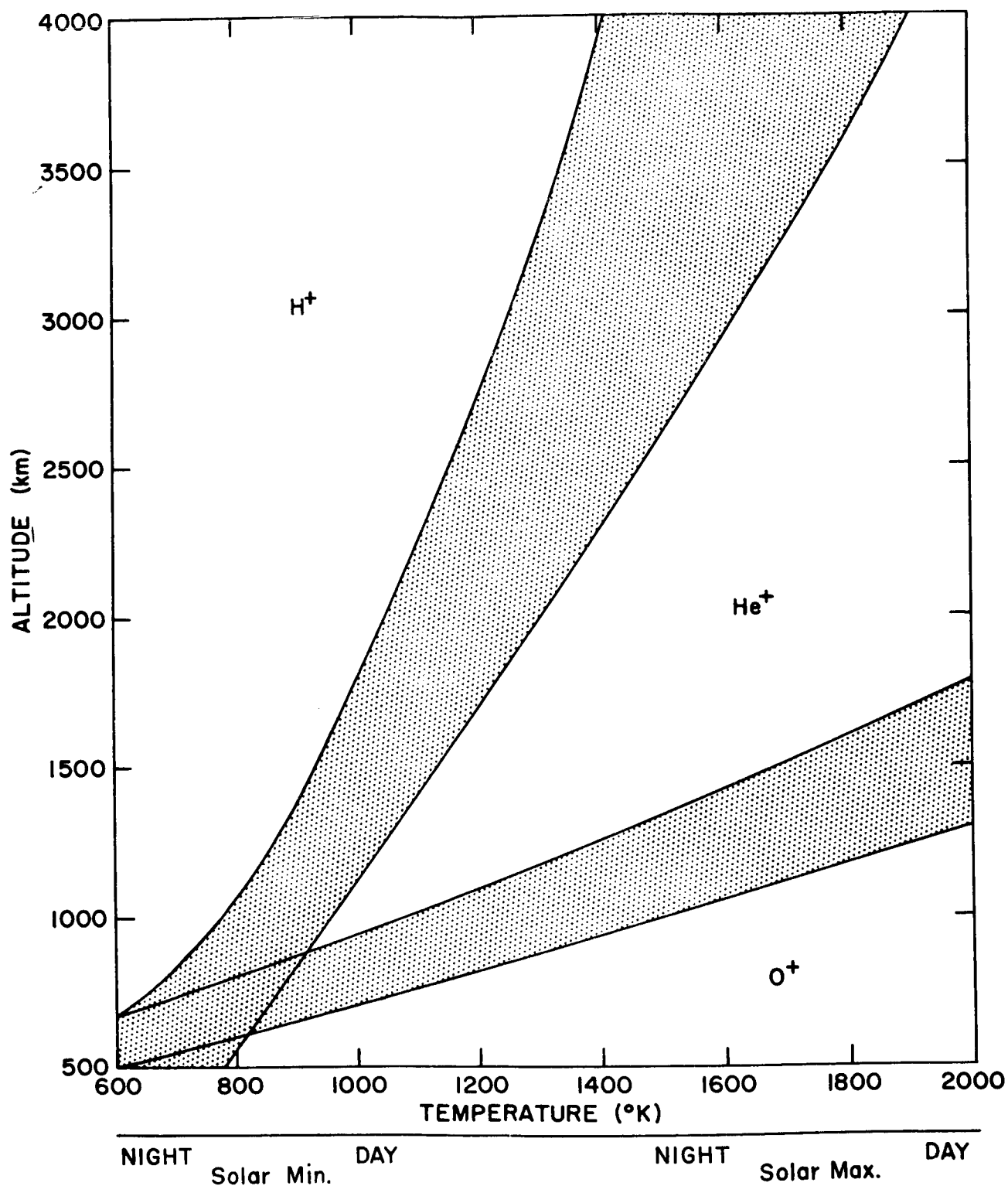Figure 8—Diurnal variation of abundance of H+, He+ and 0+ throughout a winter day (after Carlson and Gordon [21])

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Figure 9—Qualitative model of the altitude regions where H⁺, He⁺ and 0⁺ are the predominant ions (shaded areas indicate uncertainties in parameters used to derive model)
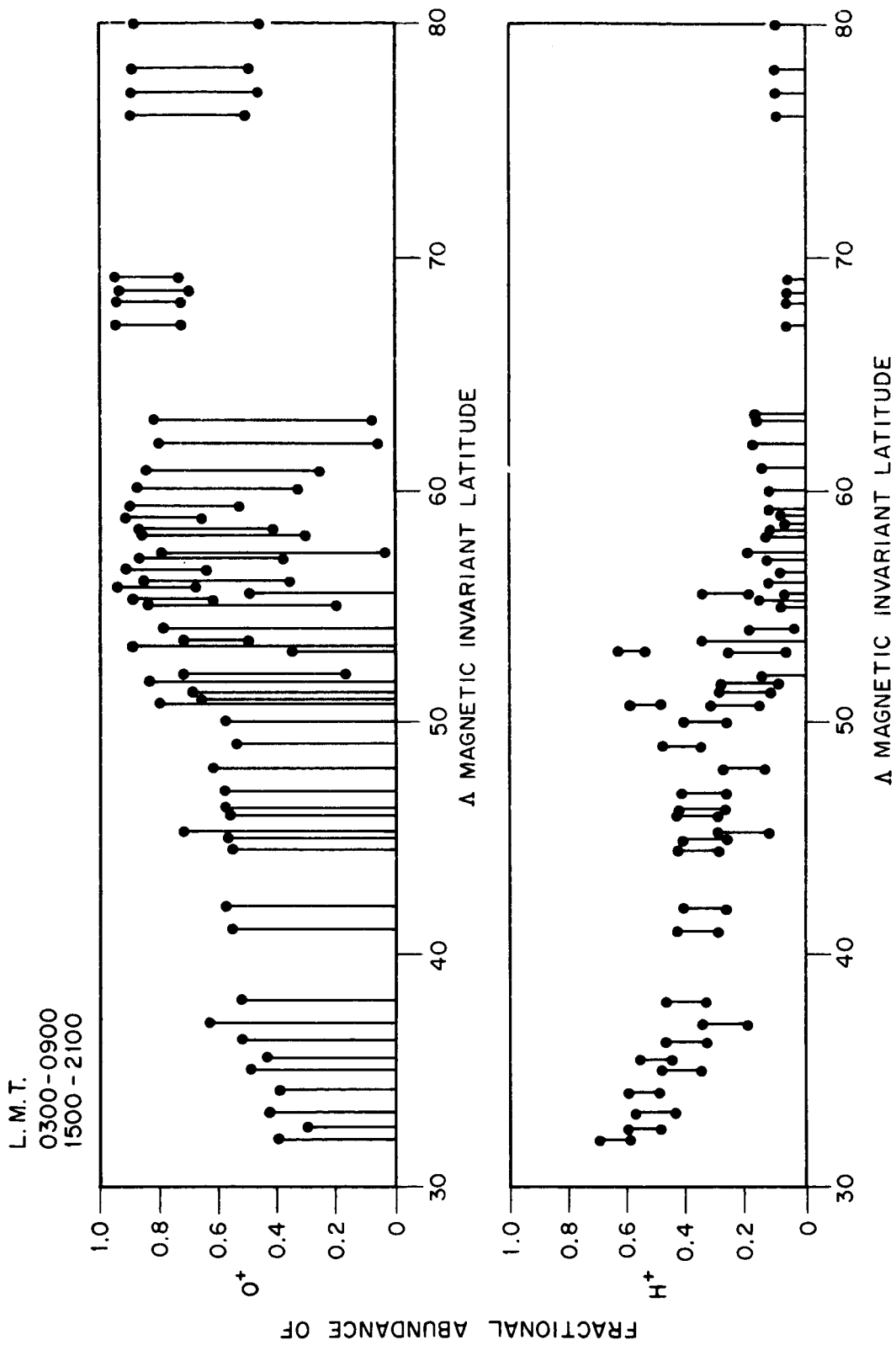
Figure 10—Ion abundance at 1000 km deduced from Alouette Ionograms and VLF resonances (after Barrington et al [32]
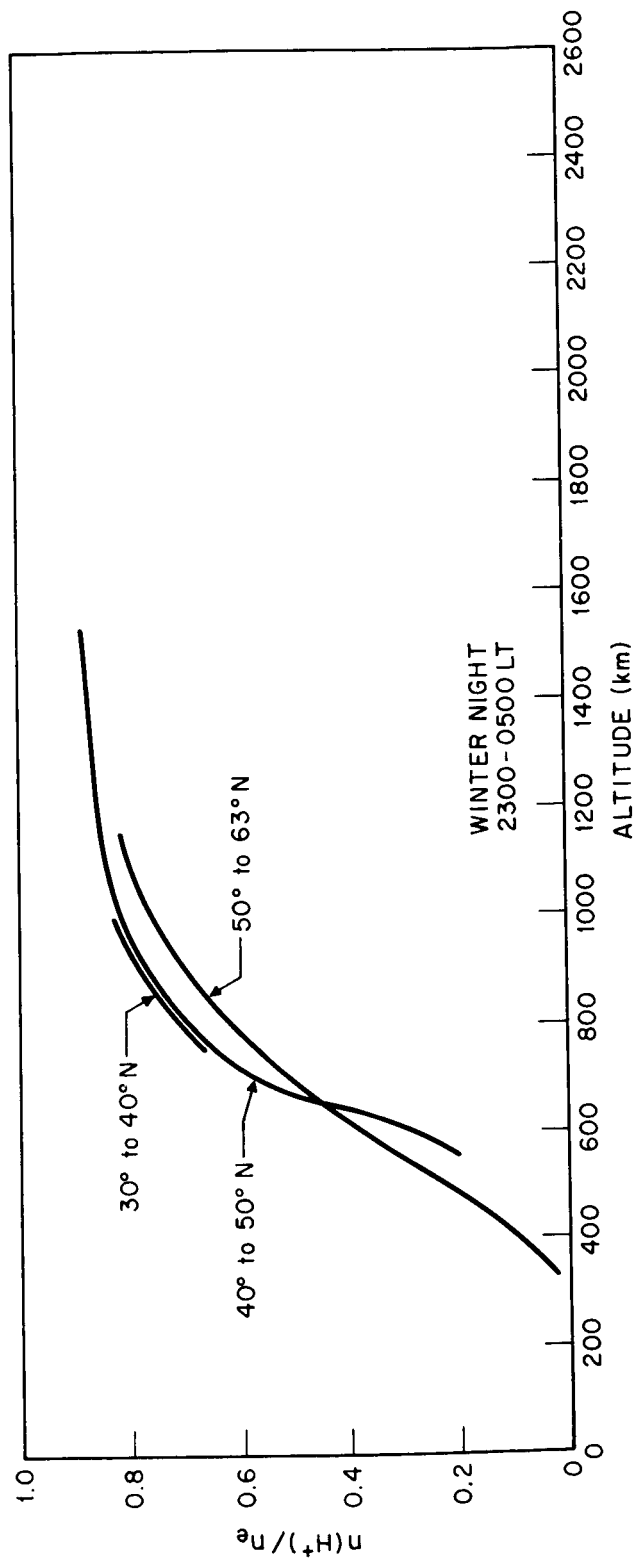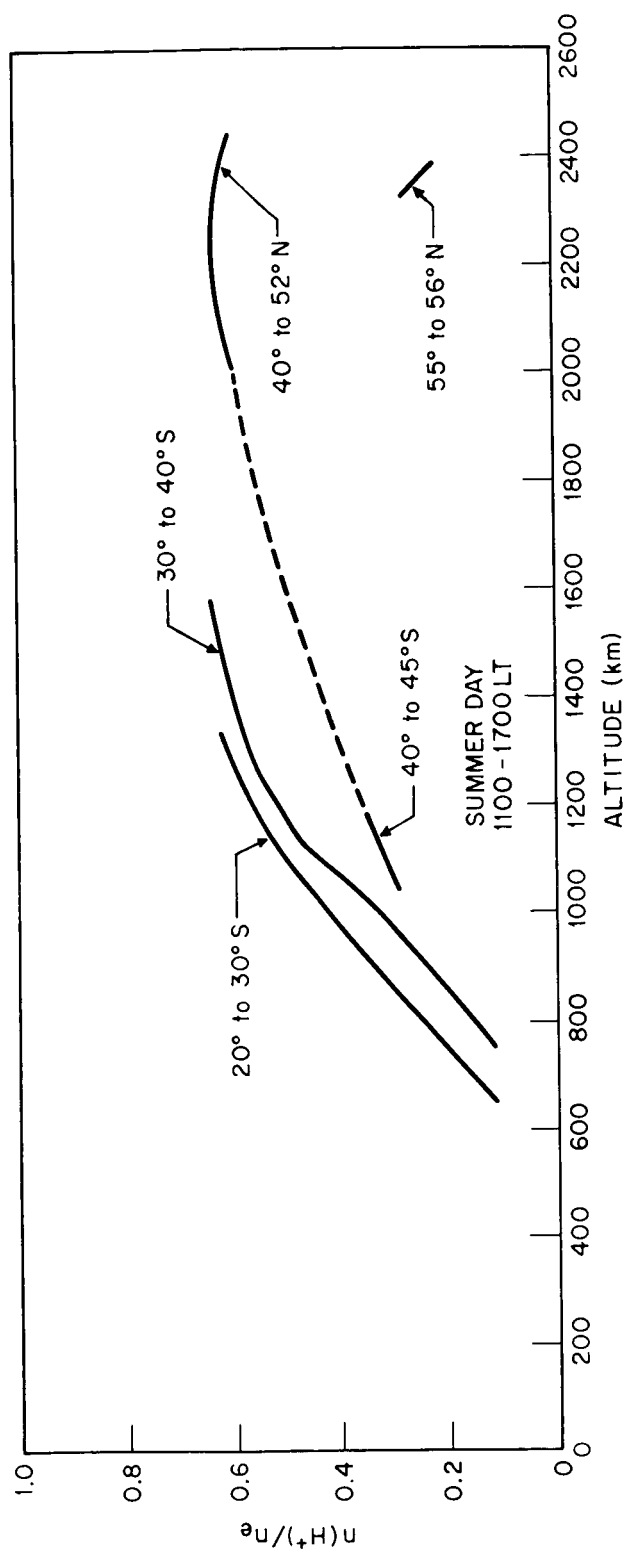
Figure 11—Magnetic latitude dependence of proton abundance vs altitude from Injun III proton-whistler measurement (after Shawhan and Gurnett [33])

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