

MARTIAN IONOSPHERE: A COMPONENT DUE TO SOLAR PROTONS

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Martian Ionosphere: A Component Due to Solar Protons

Abstract. The small magnetic field strength observed by Mariner 4 near Mars suggests that protons from the solar wind may enter the Martian atmosphere and produce ionization in addition to that produced by ultraviolet light and x-rays. It is found that solar protons produce a thin ionized layer at a rate $\sim 3 \times 10^3 \text{ cm}^{-3} \text{ sec}^{-1}$ at a depth corresponding to the F_1 region in the terrestrial atmosphere. Unless the effective recombinative coefficient is very large ($> 10^{-5} \text{ cm}^3 \text{ sec}^{-1}$), or unusual diffusion effects are present, this layer should have been detected by Mariner 4, and therefore must be present in one of the observed ionized regions. Because of its very compact shape, the subsidiary maximum near 95 km discovered in the Mariner-4 occultation experiment may be the proton ionization peak. If so, the major 120-km maximum is an F_2 layer. Distinction between photon and proton ionization regions can be made by microwave occultation experiments aboard planetary orbiters.

In the Mariner 4 S-band occultation experiment (1), a peak electron density, $n_e = 9 \pm 1 \times 10^4 \text{ cm}^{-3}$, was detected at an altitude of $120 \pm 5 \text{ km}$ during immersion in the dayside ionosphere. A subsidiary maximum at about 95 km with a peak electron density of $2 \text{ or } 3 \times 10^4 \text{ cm}^{-3}$ was also observed (Fig. 1). An upper limit $\sim 5 \times 10^3 \text{ cm}^{-3}$ was obtained for the emersion electron density in the nightside ionosphere. The electron scale height above 120 km is $24 \pm 3 \text{ km}$. Assuming, as seems very plausible, that this region is the topside of a Chapman or Bradbury layer, the neutral scale height above 120 km is about 12 km (assuming equality of electron and neutral temperatures). The resulting temperatures range from 80 to about 200° K , depending on composition, the lower value obtaining for pure atomic oxygen. Several attempts have been made (see, e. g., 2 - 6) to interpret these observations in terms of photoionization and dissociative recombination with charge exchange. In many models extreme difficulties are encountered in generating the low

temperatures deduced from the occultation data, and it has been suggested (7) that the scatter in the occultation data permits an increasing scale height above the 120-km level. This, however, has been denied by the experimenters (8). Depending on whether the 120-km peak is interpreted as an E, F₁, or F₂ region, the molecular loading density above this level ranges from 10^{14} to 10^{19} cm⁻² (1, 6, 7).

None of the models to date has considered the contribution of protons from the solar wind to the ionization of the Martian atmosphere. An examination of solar proton ionization of the atmosphere of Venus, in a test of the free-free transition model of the microwave emission, has been published elsewhere (9). A previous study (10) of proton interaction with the Martian atmosphere in an examination of one model of the blue haze was restricted to energies greater than 1 mev. A typical value for the energy of a proton in the solar wind is 1 kev. The critical value of the Martian equatorial surface magnetic field strength such that the planetary magnetic energy density is less than the kinetic energy density of the solar wind is easily shown to be $B \leq 5 \times 10^{-4}$ gauss. From the absence of radiation belts around Mars, as found by Mariner 4, an upper limit to B of 1 to 2×10^{-3} gauss has been set (11); negative results from the magnetometer aboard the same spacecraft give an upper limit of 1×10^{-3} gauss (12). While it is possible that a Martian magnetopause lies between the distance of closest approach of the Mariner 4 space vehicle and the planetary surface, this is undemonstrated and implausible; it is much more likely (11, 12) that the solar wind enters the Martian atmosphere.

Typical energies of protons in the solar wind have been measured by the Mariner 2 spacecraft (13). Their anticipated flux at Mars can be calculated using a semi-empirical scaling model for the solar wind (14). These results are given in the first two columns of Table 1. In a paper that came to our attention after the calculations of the present paper were completed, Dessler (15) has suggested that a standing shock wave is established by the interaction

of the solar wind with a preexisting highly conductive Martian ionosphere, at a distance of about 1,000 km from the surface. Downwind from the shock front, the energy is equipartitioned between solar wind protons and electrons. The net result is to decrease the total energy available to the protons by a factor two, and to increase somewhat the energy dispersion of protons entering the Martian atmosphere (15) over the values considered in this paper. The resulting corrections are of second order, and are neglected in the following discussion.

Table 1. Flux and range of solar protons in the Martian atmosphere.

E (kev)	Flux ($10^8 \text{ cm}^{-2} \text{ sec}^{-1}$)	Percent of total flux	w (cm-atm)
0.76	0.36	18.3	3.3×10^{-3}
1.14	0.47	22.5	4.5×10^{-3}
1.65	0.52	30.5	5.9×10^{-3}
2.50	0.63	19.9	7.9×10^{-3}
3.70	0.08	0.3	10.6×10^{-3}

We anticipate that, as is usually the case, the ionization cross section is larger than the charge exchange cross section for kev protons in the Martian atmosphere. Except for such noble gases as helium, argon, and xenon, all plausible major constituents of the Martian atmosphere require about 34 ev for the production of an ion pair, a result remarkably independent of the energy, mass, and charge of the incident particle (16). To the extent that such noble gases as helium and argon are radiogenic, produced by the decay

of potassium, uranium, and thorium, their concentration on Mars should be small; uranium, thorium, and potassium are concentrated near the surface of the Earth because of differentiation, and Mars is expected to be less differentiated than is the Earth (17). Even if noble gases are a predominant constituent of the Martian atmosphere, the energy required for ion-pair production is changed by less than 50 percent (16).

The range of solar protons in the Martian atmosphere is taken as $w = 4.1 \times 10^{-3} \text{ E (kev)}^{0.73} \text{ cm-atm}$, a slight extrapolation (9) from the empirical relation determined for protons in air (18); numerical results are given in the fourth column of Table 1. The protons are seen to penetrate to a depth of some $3 \times 10^{-3} \text{ cm-atm}$, equivalent to a loading density $\sim 10^{17}$ molecules cm^{-2} . Because of the exponential increase of density with depth in the upper Martian atmosphere, and because of the clustering of ion pairs at the end of the ionization track produced by a charged particle in a gas, the bulk of the ionization produced by solar protons on Mars will be concentrated at this level. The number densities correspond to the F_1 layer in the terrestrial ionosphere. The maximum ultraviolet and x-ray absorption cross sections of many plausible constituents of the Martian atmosphere are $\sim 10^{-17} \text{ cm}^2$ and it follows that there should be intermingled photon (1, 2) and proton F-region ionization on Mars. The energy flux of the solar wind at Mars is $\approx 0.45 \text{ ergs cm}^{-2} \text{ sec}^{-1}$, comparable to the ultraviolet flux, exclusive of H Ly α , which produces ionization in the terrestrial ionosphere.

We can obtain a rough estimate of the ionization rate due to protons and the resulting electron density as follows: The energy flux (cf. Table 1) divided by 34 eV per ion pair yields an ionization rate of some $1.5 \times 10^9 \text{ cm}^{-2} \text{ sec}^{-1}$. With a neutral scale height of 12 km, the resulting volume ionization rate is $q \sim 10^3 \text{ cm}^{-3} \text{ sec}^{-1}$. The peak electron density will be $n_e \approx (q/\alpha_e)^{1/2}$, where α_e is the effective recombination rate. When the principal loss mechanism is ion-electron recombination, $dn_e/dt = q - \alpha_e n_e^2$. The local time difference between immersion and emersion on Mars was ≈ 12 hours. The solution of the foregoing differential equation for $q = 0$, combined with the observed value of n_e for immersion and the upper limit for

emersion, leads to $\alpha_e > 10^{-9} \text{ cm}^3 \text{ sec}^{-1}$; i. e., recombination is dissociative and not radiative, as already expected from the presence of CO_2 and the probable presence of N_2 in the Martian atmosphere. If we take a typical value such as $\alpha_e \sim 10^{-7} \text{ cm}^3 \text{ sec}^{-1}$, we find a predicted electron density due to ionization by solar protons $\sim 10^5 \text{ cm}^{-3}$. For this solar proton ionosphere to be undetectable by Mariner 4, the recombination coefficient must be $> 10^{-5} \text{ cm}^3 \text{ sec}^{-1}$, a very large and unlikely (19) value, or diffusion and turbulence must be unusually effective in dispersing the layer. The Mariner-4 occultation experiment essentially viewed the entire Martian atmosphere from the surface to infinity with sensitivity adequate to detect $n_e \sim 10^4 \text{ cm}^{-3}$. The only such peaks observed were those at 120 and at 95 km. We conclude that the ionization peak due to solar protons lies in the observed ionized regions.

In a more detailed analysis of solar wind ionospheres on Mars we consider four isothermal models, each assuming diffusive equilibrium of the Martian upper atmosphere above 90 km. The composition of these models is given in Table 2. In each model the composition is specified and the scale height of neutral constituents determines the temperature. Figures 2 and 3 illustrate the resulting electron-density profiles, computed as in (9); they are shown as functions of the number density at the level where the high-energy tail of the solar proton wind is thermalized, and of composition. Were the Mariner 2 spectrometric data treated as discrete monoenergetic proton fluxes, the resulting ionization curves would have a jagged appearance. Actually for each energy-to-charge ratio the proton spectrometer aboard Mariner 2 accepted a fairly broad energy band. Proper weighting of the observed flux by the effective slit function and smoothing of the spectrum to account for those energies falling between the array of fixed slits (and not subsequently observed) lead to a smooth ionization rate falling within the envelope defined by the five spectrometer channels. Such a smoothing has been performed in the construction of Figs. 2 and 3.

Table 2. Mixing ratios of four adopted model atmospheres.

Model	CO ₂	Mixing Ratio		
		CO	O	N ₂
A	0	0.50	0.50	0
B	0.33	0.33	0.33	0
C	0	0.25	0.25	0.50
D	0.16	0.16	0.16	0.50

We note from these figures that the half-width at half maximum of an electron layer produced by solar protons on Mars tends to be about 3 to 8 km, i. e., considerably more compact than the usual layer produced by photo-ionization. The subsidiary maximum in the electron density near 95 km in the Mariner 4 data set also exhibits such a compact form. There is little doubt about the reality of this subsidiary maximum (8). With an observed peak electron density at the secondary maximum of 2 or $3 \times 10^4 \text{ cm}^{-3}$ and the values of q given in Figs. 2 and 3, a value of α_e of several times $10^{-6} \text{ cm}^3 \text{ sec}^{-1}$ is indicated. These values are within the range of dissociative recombination coefficients reported in the literature (19). From the observed shape of this maximum, the neutral number density in its vicinity must be several times 10^{11} cm^{-3} (Fig. 2). For the incident protons to produce peak ionization at this depth, the loading density is specified (cf. Fig. 4) and indicates $\sim 10^{17} \text{ molecules cm}^{-2}$ above 95 km; the 120-km peak must then be an F₂ and not an E or F₁ layer. In this case, the question of the apparent absence of an E layer naturally arises. Large values of α_e below 90 km can be invoked in explanation. It has recently been suggested (20) that the occultation data are consistent with an additional electron density maximum at an altitude of some 12 km; but the resulting small pressures of the neutral gas implied if this is an E-region are inconsistent with the surface pressures.

The contention of the present paper — that some component of the observed Martian ionosphere, perhaps the subsidiary maximum at 95-km altitude, is due to penetration of protons from the solar wind into the Martian atmosphere — can be tested by future observations. The proton ionization should be more nearly isotropic and much more time-variable than the electromagnetic contribution. Therefore, observations at a range of local times during a Martian day, and over a period including several solar events, seem indicated. Such observations cannot readily be performed by a flyby vehicle, but represent a natural radio occultation experiment for a small Mars orbiter. The low surface magnetic field strength of Venus suggests that solar protons also may be producing ionization in the atmosphere of that planet (9). Forthcoming flyby and projected orbiter radio occultation experiments near Venus will be useful in examining this possibility.

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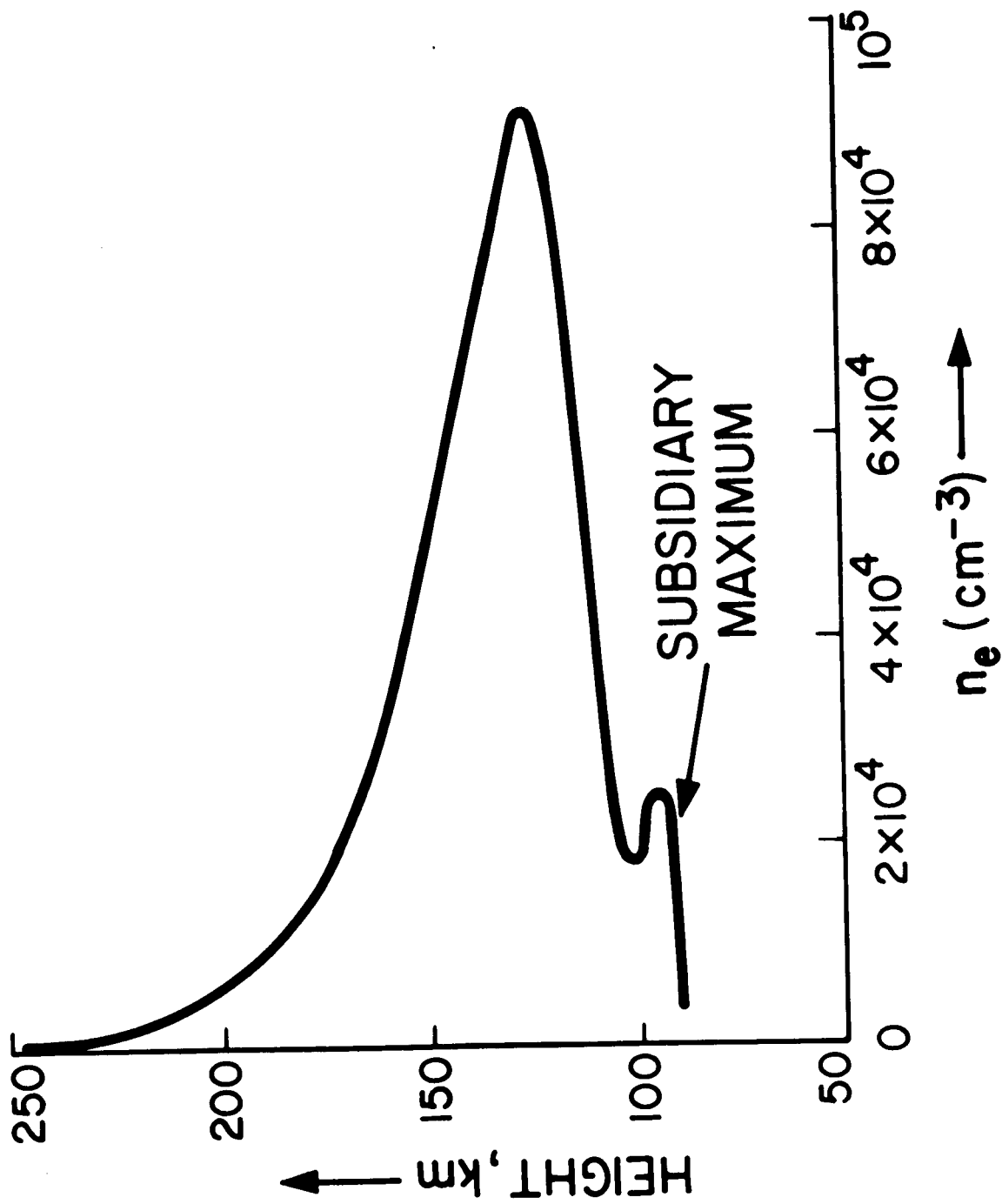


Fig. 1. Electron density profile during ingress, Mariner 4 occultation experiment (cf. 1).

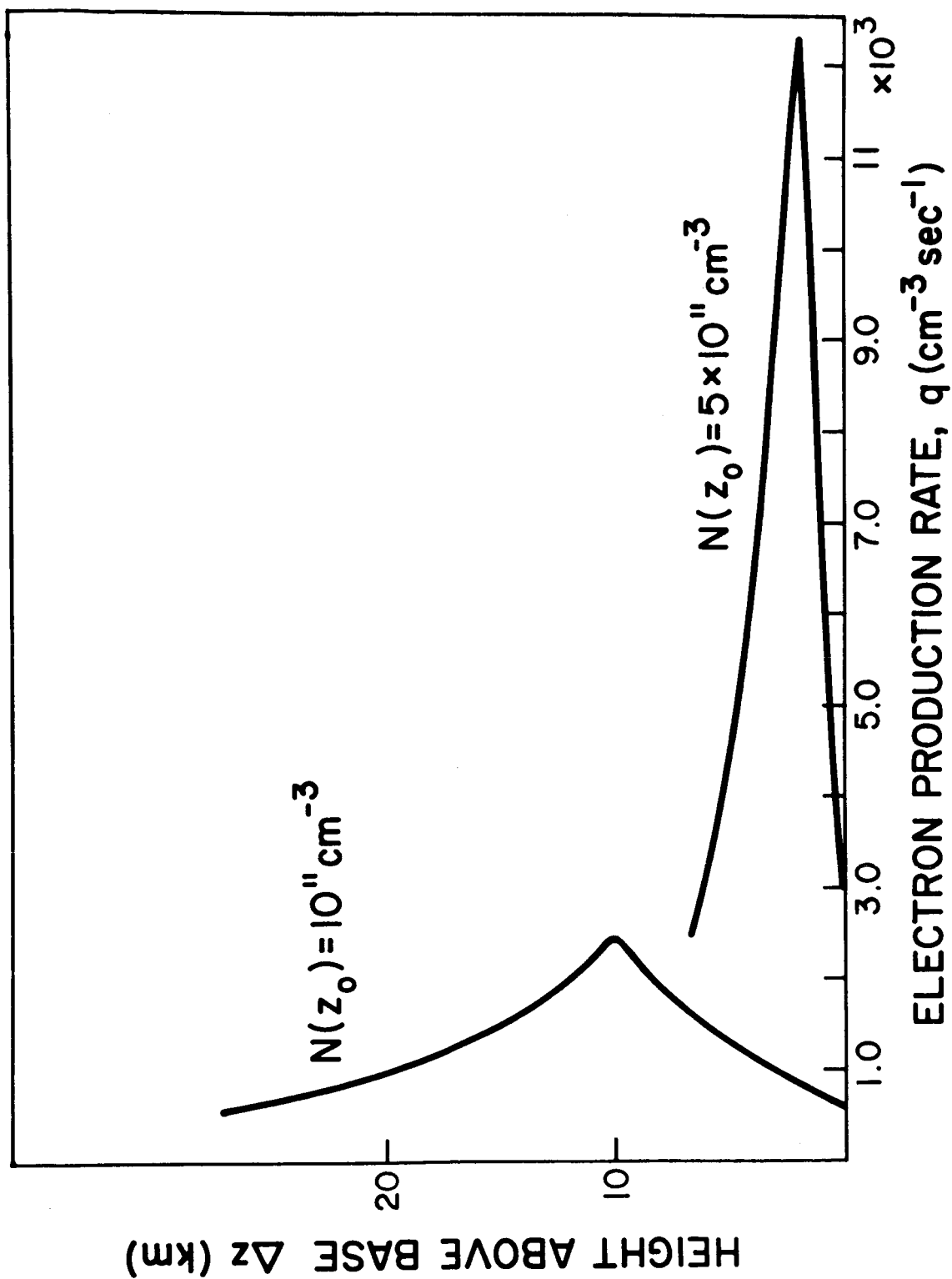


Fig. 2. Computed solar proton ionospheres for two different choices of $n(z_0)$, the neutral number density at the base level of the ionized region.

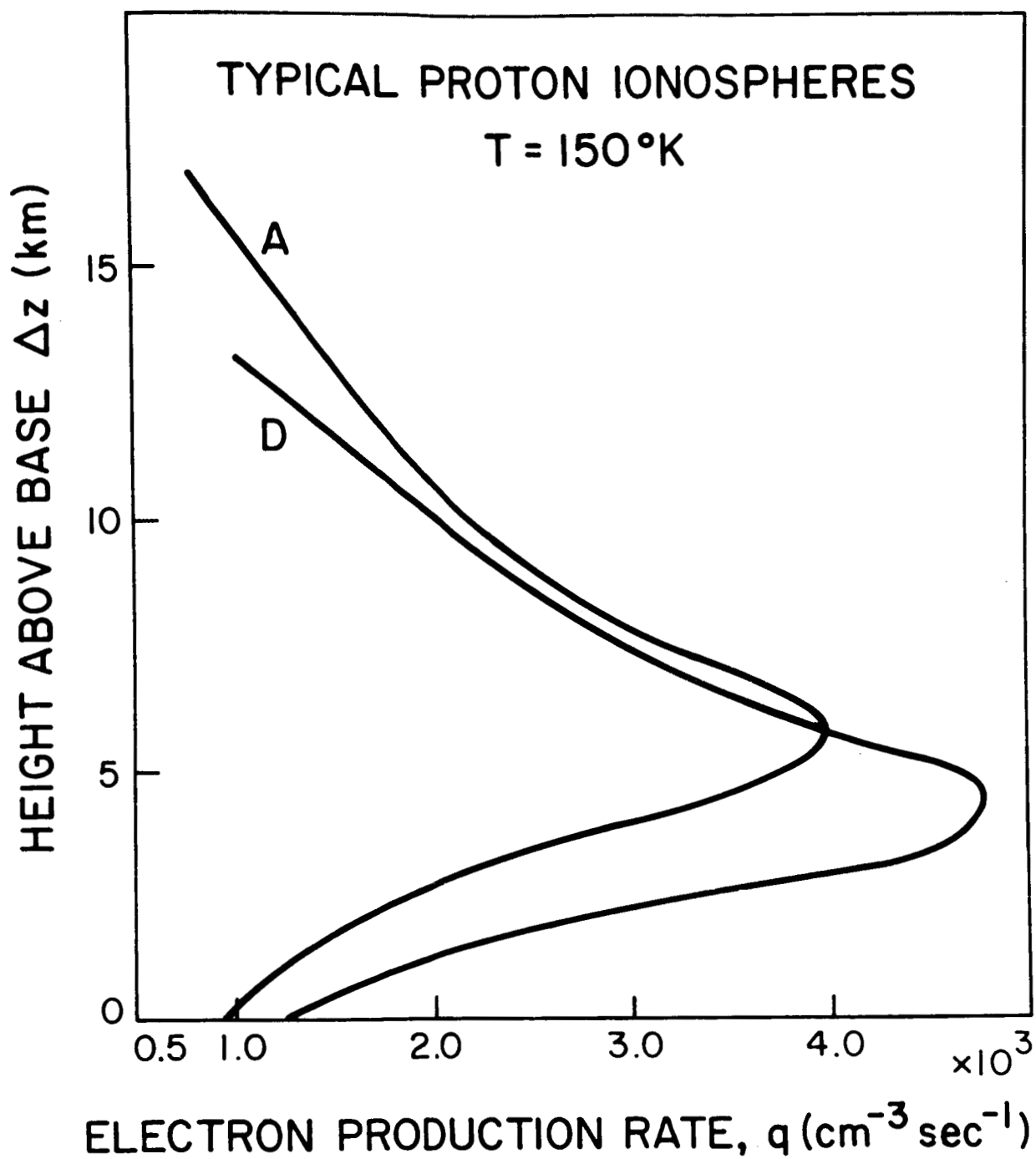


Fig. 3. Computed solar proton ionospheres for two different choices of atmospheric composition. Models B and C (cf. Table 2) give curves intermediate between those shown. $T = 150^\circ \text{K}$ is assumed.

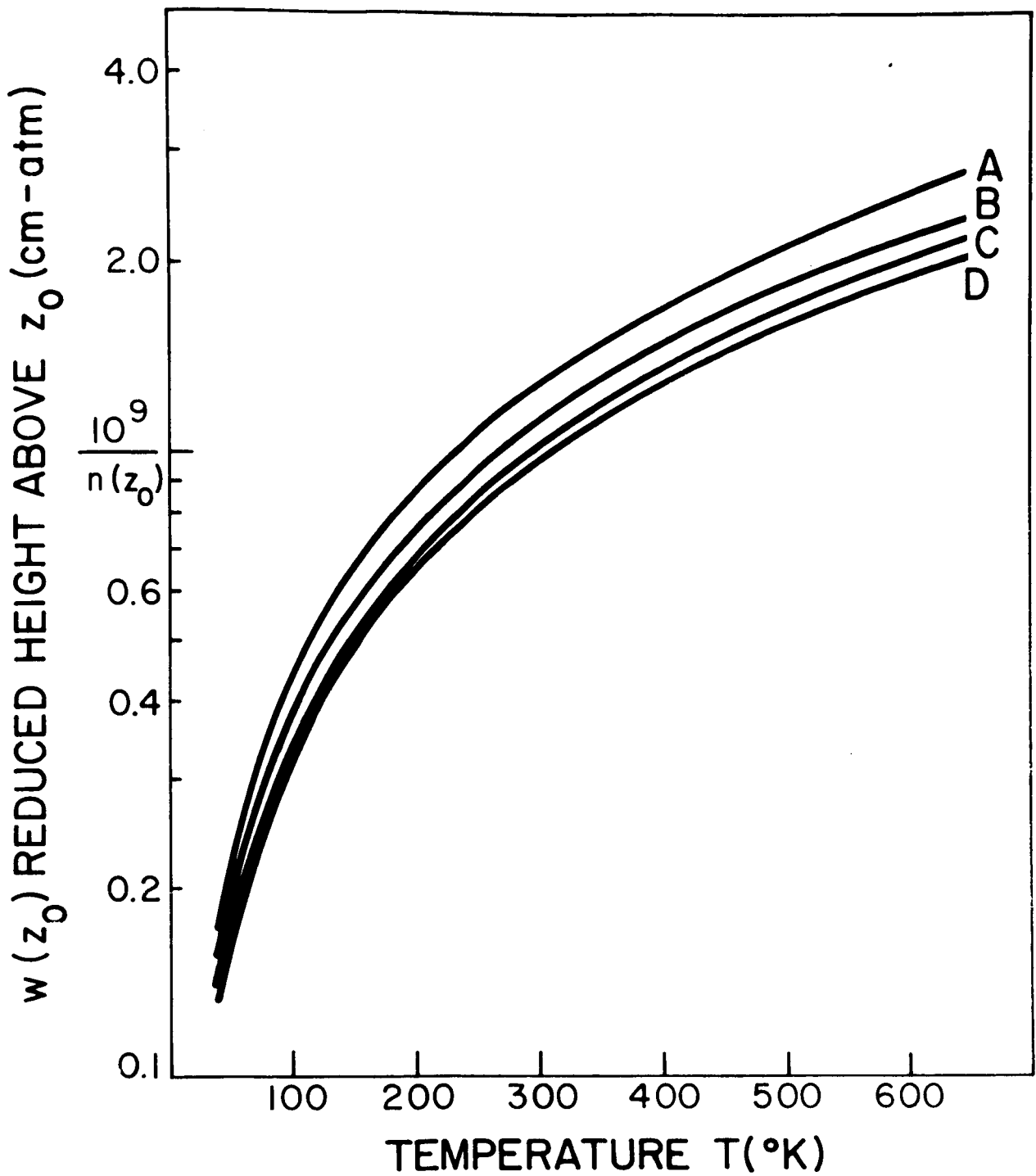


Fig. 4. Reduced height of the Martian atmosphere above base level z_0 as a function of temperature and composition.

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