Reports

Martian Ionosphere: A Component Due to Solar Protons

Abstract. *The small magnetic field strength observed near Mars by Mariner IV 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 of the order of 3×10^3 per cubic centimeter per second at a depth corresponding to the F_1 region in the terrestrial atmosphere. Unless the effective recombinative coefficient is very large (greater than 10^{-5} centimeter cubed per second) or unless unusual diffusion effects are present, this layer should have been detected by Mariner IV, and therefore must be present in one of the observed ionized regions. Because of its very compact shape, the subsidiary maximum near 95 kilometers discovered in the Mariner-IV occultation experiment may be the proton ionization peak. If so, the major 120-kilometer 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-IV S-band occultation experiment (*1*), a peak electron density, $n_e = 9 \pm 1 \times 10^4$ cm^{-3}, was detected at an altitude of 120 ± 5 km during immersion in the dayside ionosphere. A subsidiary maximum at about 95 km, with a peak electron density of 2 or 3×10^4 cm^{-3}, was also observed (Fig. 1). An upper limit of $\sim 5 \times 10^3$ cm^{-3} was obtained for the emersion electron density in the nightside ionosphere. The electron scale height above 120 km is 24 ± 3 km. If we assume, 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 (for equal 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, for example, *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 these 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, F_1, or F_2 region, the integrated density above this level ranges from 10^{14} to 10^{19} cm^{-2} (*1, 6, 7*).

So far none of the models has considered the contribution of protons from the solar wind to ionization of the Martian atmosphere. An examination of the ionization of the atmosphere of Venus by solar protons, 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 magnetic field strength at the Martian equatorial surface required so that the planetary magnetic energy density is less than the kinetic energy density of the solar wind is easily shown to be $B \leqq 5 \times 10^{-4}$ gauss. From the absence of radiation belts around Mars, as found by Mariner IV, 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 IV space vehicle and the planetary surface, this has not been demonstrated and is 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 II spacecraft (*13*). Their anticipated flux at Mars can be calculated with a semiempirical scaling model for the solar wind (*14*). These results are given in the first columns of Table 1. In a paper that came to our attention after the calculations of this report 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 1000 km from the surface. Downwind from the shock front, the energy is equipartitioned between protons and electrons of the solar wind. The net result is to decrease the total energy available to the protons by a factor of 2, and to increase somewhat the energy dispersion of protons entering the Martian atmosphere (*15*) over the values considered in this report. The resulting corrections are of second order, and are neglected in the following discussion. We have also neglected ionization by solar alpha particles which often have a flux of 5 to 20 percent of that of solar protons. If the alpha particles have the same velocity distribution as the protons, they will tend to increase the ionization due to charged particles by a factor of approximately 2 or less.

We anticipate that, as is usually the case, the ionization cross section is larger than the charge-exchange cross section for kilovolt 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 (being 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 Earth because of differentiation, and Mars is expected to be less differentiated than Earth is (*17*). Even

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

Energy (kev)	Flux (10^8 cm^{-2} sec^{-1})	Percent of total flux	Range (cm-atm)
0.76	0.36	18.3	3.3×10^{-3}
1.14	.47	22.5	4.5×10^{-3}
1.65	.52	30.5	5.9×10^{-3}
2.50	.63	19.9	7.9×10^{-3}
3.70	.08	0.3	10.6×10^{-3}

if noble gases are a predominant constituent of the Martian atmosphere, the energy required for the production of ion pairs is changed by less than 50 percent (*16*).

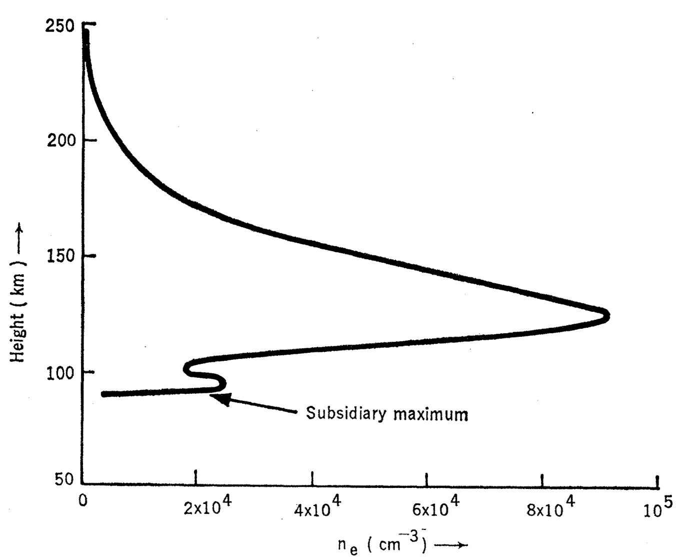
The range of solar protons in the Martian atmosphere is taken as $w = 4.1 \times 10^{-3}$ $[E \text{ (kev)}]^{0.73}$ cm-atm, a slight extrapolation (*9*) from the empirical relation determined for protons in air (*18*) (see Table 1). The protons are seen to penetrate to a depth of some 3×10^{-3} cm-atm, equivalent to an integrated density of the order of 10^{17} molecules per square centimeter column. 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 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 cross sections for ultraviolet and x-ray absorption of many plausible constituents of the Martian atmosphere are of the order of 10^{-17} cm^2, and it follows that there should be intermingled photon (*1, 2*) and proton ionization in the F region of Mars. The energy flux of the solar wind at Mars is $\simeq 0.45$ erg cm^{-2} 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 rate of ionization due to protons and the resulting electron density as follows. The energy flux (see Table 1) divided by 34 ev per ion pair yields an ionization rate of about 1.5×10^9 cm^{-2} sec^{-1}. With a neutral scale height of 12 km, the resulting volume ionization rate is $q \sim 10^3$ cm^{-3} sec^{-1}. The peak electron density will be $n_e \simeq (q/\alpha_e)^{\frac{1}{2}}$, where α is the effective recombination rate. When the principal mechanism of loss is ion-electron recombination, $dn_e/dt = q - \alpha_e n_e^2$. The local time difference between immersion and emersion on Mars was approximately 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 a value for α_e of more than 10^{-9} cm^3 sec^{-1}; that is, recombination is dissociative and not radiative, as already expected from the presence of carbon dioxide and the probable presence of nitrogen in the Martian atmosphere. If we take a typical value such as $\alpha_e \sim 10^{-7}$ cm^3 sec^{-1}, we find a predicted electron density due to ionization by solar protons of the order of 10^5 cm^{-3}. For this solar proton ionosphere to be indetectable by Mariner IV, the recombination coefficient would have to be $> 10^{-5}$ cm^3 sec^{-1}, a very large and unlikely (*19*) value, or diffusion and turbulence would have to be unusually effective in dispersing the layer. The Mariner-IV occultation experiment essentially viewed the entire Martian atmosphere from the surface to infinity with sensitivity adequate to detect a value for n_e of the order of 10^4 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.

Table 2. Mixing ratios in four adopted model atmospheres.

Model	Mixing ratio			
	CO_2	CO	O	N_2
A	0	0.50	0.50	0
B	0.33	.33	.33	0
C	0	.25	.25	0.50
D	0.16	.16	.16	.50

In a more detailed analysis of solar wind ionospheres on Mars we consider four isothermal models, each of which assumes a 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 show the resulting electron-



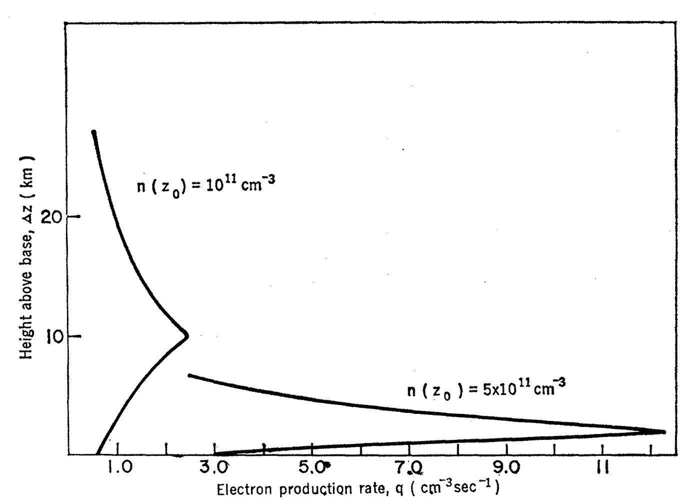


Fig. 1 (left). Electron density (n_e) profile during ingress, Mariner IV occultation experiment (see *1*). Fig. 2 (right). Computed solar proton ionospheres for two different choices of $n(z_0)$, the neutral number density, at the base level of the ionized region. Values on the abscissa must be multiplied by 10^3.

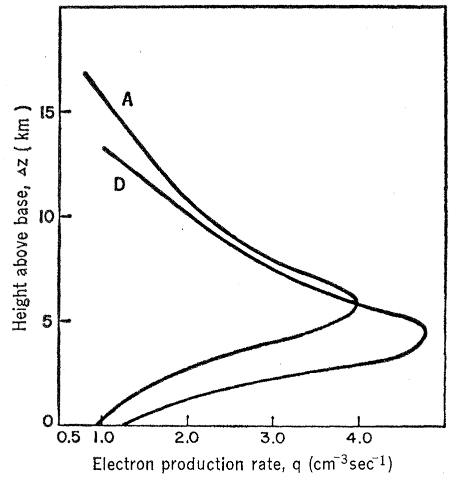


Fig. 3. Computed solar proton ionospheres for two different choices of atmospheric composition. Models B and C (see Table 2) give curves intermediate between those shown. Curves A and D, representing typical proton ionospheres, correspond to models A and D in Table 2. A temperature of 150°K is assumed. Values on the abscissa must be multiplied by 10^3.

density profiles, computed as in the paper by Walker and Sagan (*9*); they are shown as a function of the number density at the level where the high-energy tail of the solar proton wind is thermalized, and as a function of composition. Were the Mariner II spectrometric data treated as discrete monoenergetic fluxes of positive ions, the resulting ionization curves would have a jagged appearance. Actually, for each energy-to-charge ratio, the positive-ion spectrometer aboard Mariner II 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 peaks (the gaps were determined by geometry and by the voltage of the analyzer) lead to a smooth ionization rate that falls within the envelope defined by the five effective spectrometer channels. Such a smoothing has been performed in the construction of Figs. 2 and 3. It is assumed that any high-energy tail, $E > 5$ kev, represents a very small fraction of the total flux (see Table 1). Any high-energy tail will tend to increase somewhat the ionization at levels below the ionization maximum (see Figs. 3 and 4).

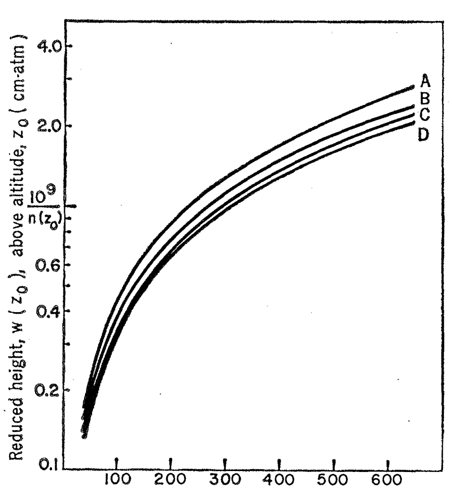


Fig. 4. Reduced height of the Martian atmosphere above base level z_0 as a function of temperature and composition. Curves A, B, C, and D correspond to the models in Table 2.

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, that is, considerably more compact than the usual layer produced by photoionization. The subsidiary maximum in the electron density near 95 km in the Mariner IV data also exhibits such a compact form. There is little doubt about the reality of this subsidiary maximum (*8*). With an observed electron density peak at the secondary maximum of 2 or 3×10^4 cm^{-3} and the values of q given in Figs. 2 and 3, a value of α_e of several times 10^{-6} cm^3 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} (see Fig. 2). For the incident protons to produce peak ionization at this depth, the loading density is specified (see Fig. 4) and indicates a value of the order of 10^{17} molecules per square centimeter column above 95 km; the 120-km peak must then be an F_2, and not an E or F_1, layer. In this case, the question of the apparent absence of an E layer naturally arises. Large values of α_e below 90 km might 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 about 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 this report—that some component of the observed Martian ionosphere, perhaps the subsidiary maximum at an altitude of 95 km, 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 may also be producing ionization in the atmosphere of that planet (*9*). Forthcoming radio occultation experiments near Venus by flyby and projected orbiter vehicles will be useful in examining this possibility.

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References and Notes

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12 May 1967