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CONCENTRATION OF HYDROGEN IN THE UPPER ATMOSPHERE OF THE EARTH IN THE 300 —600 KM ALTITUDE RANGE ACCORDING TO IONOSPHERIC DATA

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SUMMARY

Utilizing the results of rocket and satellite investigations of the ionic composition of the outer part of the F_2-region of the ionosphere and of measurements of atomic oxygen concentration at corresponding heights, estimates are presented of hydrogen concentration in the 300 - 600 km altitude range during solar activity minimum. Comparison is also made between the estimated values of hydrogen concentration and the results of direct measurements.

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* *

According to data of ionosphere investigations, the altitude distribution of neutral hydrogen concentration n(h, H) may be estimated from measurements of the ionic composition of the medium, in particular of hydrogen ion H^+ concentrations, the latter forming and vanishing in the course of reactions of asymmetrical resonance transfer of the charge [1]

$$H + O^+ \rightleftarrows H^+ + O \tag{1}$$

and of atomic oxygen O^+. These estimates are based upon the equation

$$\frac{\partial n(H^+)}{\partial t} = S(H^+) - L(H^+) - \frac{\partial F(H^+)}{\partial h}, \tag{2}$$

determining the altitude-time distribution $n(H^+)$. In equation (2)

$$S(H^+) = k(H, O^+)n(H)n(O^+),$$
$$L(H^+) = k(H^+, O)n(H^+)n(O),$$
$$F(H^+) = n(H^+)u(H^+) \simeq -D(H^+)\left(\frac{\partial n(H^+)}{\partial h} + \frac{n(H^+)}{H(H^+)}\right) \tag{3}$$

represent respectively the source, the losses and flux of ions H^+: $\underline{k}$ are the coefficients of reactions rates (1), $u(H^+)$ is the vertical velocity component of the directed motion of protons, $D(H^+)$ is the diffusion coefficient, H is the scale height.

In the outer part of the F_2-region of the ionosphere ($h \simeq 300 - 600$ km) the settling time of chemically equilibrium distribution of ion H^+ concentration ($S = L$), determined as $\tau_1 = 1/k(H^+, O)n(O)$, constitutes a few tens or less minutes, while the settling time of diffusive equilibrium distribution $[u(H^+) = 0]$ is

$$\tau_2 \simeq H^2(\mathrm{H}^+)\,/\,D(\mathrm{H}^+) \simeq 10^3 \div 10^4 \text{ min.}$$

More detailed data on the orders of magnitudes of τ_1 and τ_2 in daytime (about 1600 hours LT) at various heights are compiled in Table 1(*):

T A B L E 1

characteristics	altitude, km				ref
	300	400	500	600	
$n(\mathrm{H}^+)/n(\mathrm{O}^+)$	$6{,}5\cdot10^{-3}$	$1{,}1\cdot10^{-2}$	$2{,}5\cdot10^{-2}$	$5{,}2\cdot10^{-2}$	[5]
$n(\mathrm{O})$, см$^{-3}$	$1{,}0\cdot10^{8}$	$1{,}6\cdot10^{7}$	$2{,}4\cdot10^{6}$	$4{,}0\cdot10^{5}$	[8]
T_i, °K	970	1100	1370	1670	[11]
T, °K	880	880	880	880	
τ_1, min	$4{,}2\cdot10^{-1}$	$2{,}6\cdot10^{0}$	$1{,}7\cdot10^{1}$	$1{,}0\cdot10^{2}$	
τ_2, min	$1{,}7\cdot10^{4}$	$9{,}3\cdot10^{3}$	$4{,}0\cdot10^{3}$	$2{,}5\cdot10^{3}$	
δ_2	$2{,}5\cdot10^{-5}$	$6{,}4\cdot10^{-5}$	$4{,}2\cdot10^{-3}$	$3{,}5\cdot10^{-2}$	
$n(\mathrm{H})$, см$^{-3}$ $(T = T_i)$	$5{,}8\cdot10^{5}$	$1{,}6\cdot10^{5}$	$5{,}6\cdot10^{4}$	$1{,}8\cdot10^{4}$	
$n(\mathrm{H})$, см$^{-3}$ $(T \neq T_i)$	$5{,}5\cdot10^{5}$	$1{,}4\cdot10^{5}$	$4{,}5\cdot10^{4}$	$1{,}3\cdot10^{4}$	
$n(\mathrm{H})$, см$^{-3}$ $(T = 860°\mathrm{K})$	$7{,}60\cdot10^{4}$	$6{,}50\cdot10^{4}$	$5{,}60\cdot10^{4}$	$4{,}98\cdot10^{4}$	[12]
$n(\mathrm{H})$, см$^{-3}$ $(T = 838°\mathrm{K})$	$3{,}20\cdot10^{4}$	$2{,}82\cdot10^{4}$	$2{,}49\cdot10^{4}$	$2{,}21\cdot10^{4}$	[13]
$n(\mathrm{H})$, см$^{-3}$ $(T = 990°\mathrm{K})$	$2{,}30\cdot10^{4}$	$2{,}06\cdot10^{4}$	$1{,}86\cdot10^{4}$	$1{,}67\cdot10^{4}$	[13]
$n(\mathrm{H})$, см$^{-3}$ $(T = 1000°\mathrm{K})$	—	—	$2{,}70\cdot10^{4}$	—	[14]
$n(\mathrm{H})$, см$^{-3}$ $(T = 1000°\mathrm{K})$	—	—	$7{,}5\cdot10^{4}$	—	[15]

On the other hand, at considered heights, the term of motion in Eq.(2) is much smaller by comparison with S and L, since (see Table 1)

$$\delta_1 = \left|\frac{\partial F(\mathrm{H}^+)/\partial h}{S(\mathrm{H}^+)}\right| \simeq \frac{D(\mathrm{H}^+)n(\mathrm{H}^+)}{k(\mathrm{H},\mathrm{O}^+)n(\mathrm{O}^+)n(\mathrm{H})H^2(\mathrm{H}^+)} \ll 1,$$

$$\delta_2 = \left|\frac{\partial F(\mathrm{H}^+)/\partial h}{L(\mathrm{H}^+)}\right| \simeq \frac{D(\mathrm{H}^+)}{k(\mathrm{H}^+,\mathrm{O})n(\mathrm{O})H^2(\mathrm{H}^+)} \ll 1$$

(*) see this remark at the end of the paper.

Therefore, it is clear that in Eq.(2)

$$S(\mathrm{H}^+),\ L(\mathrm{H}^+) \gg \left|\frac{\partial n(\mathrm{H}^+)}{\partial t}\right|,\ \left|\frac{\partial F(\mathrm{H}^+)}{\partial h}\right|.$$

Under these conditions Eq.(2) has the following simple solutions:

$$\frac{n(\mathrm{H}^+)}{n(\mathrm{O}^+)} = \frac{9}{8}\frac{n(\mathrm{H})}{n(\mathrm{O})} \tag{4}$$

at equality of ion temperatures $T_i = T_i(H^+) = T_i(O^+)$, of neutral particles' T [6] and

$$\frac{n(\mathrm{H}^+)}{n(\mathrm{O}^+)} = \frac{9}{8}\frac{n(\mathrm{H})}{n(\mathrm{O})}\left\langle\frac{T_i(\mathrm{O}^+)/16 + T}{T_i(\mathrm{H}^+) + T/16}\right\rangle^{1/2} \tag{5}$$

for $T_i \neq T$ [7]. In the presence of information on the values of n(O), T_i, T, $n(H^+)/n(O^{\pm})$, we may estimate from (4) and (5) the value of n(h, H). For this estimate we utilize the results of measurements of the required quantities with reference to a period close to solar activity minimum.

The measurements of n(h, O) were conducted with the help of mass-spectrometers on AES "EXPLORER-17" during April and May 1963 [8]. The processing of the data related to 1100 - 2000 hours LT and the altitude range 260 - - 600 km by the method of least squares allowed us to obtain for the distribution n(h, O) the following expression:

$$n(h;\mathrm{O}) = 2{,}44\cdot 10^{10}\cdot \exp\left(-\frac{h}{54{,}4}\ \text{км}\right)[\text{см}^{-3}], \tag{6}$$

whence it is easy to find the estimate T ≃ 880°K.

Several measurements of ion composition of the outer part of the F_2-region of the ionosphere were performed by various methods, utilizing radio-frequency mass-spectrometers on AES "ELEKTRON-2" [5] (10 to 16 February 1964, h = 440 - 1800 km, t = 1400 - 1900 hours LT), of incoherent radiowave scattering [9] (December 1964 and July 1965, h = 450 - 1200 km, at middle latitudes and in magnetoquiet days) and of magnetic mass-spectrometer on a rocket [10] (17 January 1964, h = 200 - 926 km, t = 00 hours LT, at middle latitudes).

The results of calculations of two variants of n(h, H) distribution at about 1600 hours LT, related respectively to conditions $T = T_i$ and $T \neq T_i$, are compiled in Table 1. The indicated distribution of T_i was borrowed from [11]. The taking into account of ion and neutral temperatures affects little the distribution n(h, H); for example, on h ≃ 500 km, two distribution variants differ only by a factor of ∿ 1.2.

Comparison of ionospheric estimates of n(h, H) for daytime conditions with model calculations of [12-14] shows a good agreement with those of [12] for $h \simeq 500$ km [12] (see Table 1). However, the value $n(500, H) = 7.5 \cdot 10^4$ cm^{-3} at $T = 1000°K$ [15], is apparently somewhat overrated.

Let us now consider the night conditions. The data processing of [8], related to the distribution of n(h, O) in night hours (2200-0400 hours LT) in the altitude range 300 - 680 km, also applying the method of least squares, resulted in the expression

$$n(h; O) = 5{,}55 \cdot 10^{10} \cdot \exp\left(-\frac{h}{47{,}6}\right) [см^{-3}] \qquad (7)$$

[H(O) ≃ 47.6 km corresponds to thermosphere temperature T ≃ 760°K].

In the near-midnight hours $n(450, O) = 4.86 \cdot 10^6$ cm^{-3}. According to [9] at the same height $n(H^+) / n(O^+) \simeq 0.6$. Under these conditions, at midnight $n(450, H) \simeq 2.6 \cdot 10^6$ cm^{-3}.

The results of estimates of n(h, H) at midnight according to data of [10] and the expression (7) are compiled in Table 2., where we find also the estimates of n(h, H) based upon the data of [10] and other model distributions of n(h, O) [12, 13] (*)It should be noted that the distribution of n(h, O), preassigned by expression (7), agrees well with the models of [12 & 13] on the heights considered (the divergences do not exceed a factor of ∿ 2). The estimetes of n(h, H) in the near-midnight hours according to the distribution of $n(H^+) / n(O^+)$ [10] lead to values which are at least by two orders greater than the model ones [12-15].

T A B L E 2

characteristics	altitude, km			ref.
	400	450	500	
$n(H^+)/n(O^+)$	1,0	3,3	10,0	[10]
$n(O)$, $см^{-3}$	$1{,}25 \cdot 10^7$	$4{,}85 \cdot 10^6$	$1{,}52 \cdot 10^6$	[8]
$n(H)$, $см^{-3}$ $(T = T_i)$	$1{,}11 \cdot 10^7$	$1{,}40 \cdot 10^7$	$1{,}35 \cdot 10^7$	
$n(O)$, $см^{-3}$	$1{,}91 \cdot 10^7$	$5{,}57 \cdot 10^6$	$1{,}66 \cdot 10^6$	[12]
$n(H)$, $см^{-3}$	$1{,}70 \cdot 10^7$	$1{,}63 \cdot 10^7$	$1{,}48 \cdot 10^7$	
$n(H)$, $см^{-3}$ $(T = 670\ °K)$	$4{,}10 \cdot 10^5$	$3{,}75 \cdot 10^5$	$3{,}50 \cdot 10^5$	[12]
$n(O)$, $см^{-3}$	$2{,}64 \cdot 10^7$	—	$3{,}71 \cdot 10^6$	[13]
$n(H)$, $см^{-3}$	$2{,}35 \cdot 10^7$	—	$3{,}30 \cdot 10^7$	
$n(H)$, $см^{-3}$ $(T = 840\ °K)$	$2{,}82 \cdot 10^4$	—	$2{,}49 \cdot 10^4$	[13]
$n(H)$, $см^{-3}$ $(T = 750\ °K)$	—	—	$2{,}08 \cdot 10^5$	[14]
$n(H)$, $см^{-3}$ $(T = 700\ °K)$	—	—	$\sim 1{,}5 \cdot 10^5$	[15]

The experimental data on hydrogen concentration on the height considered or close to them are obtained from the observations of Lα-emission and measurements of atmosphere density. A review of data available on the distribution of n(h, H) can be found in the papers [15, 16].

(*) and the results of model calculations [12-15]

The determination of hydrogen concentration by atmosphere density leads to clearly overrated values. Thus, for example, it was obtained according to the density measured by sensors installed onboard "Explorer-17" [17] that in April-June 1963 at 900 km altitude, $n(H) \simeq 10^7$ cm^{-3}.

Mass-spectrometric observations of atmosphere composition were lately conducted on "Explorer-32" in the $h \simeq 290-1000$ km altitude range [18]. According to this report the typical value $n(H) = 2 \cdot 10^6$ cm^{-3}was regsitered at 0900 hours local time at an altitude $h \simeq 300$ km. If we combined the data of [19] with the results of our own estimates, we would obtain for $h \simeq 300$ km a daily course for n(H) ($t = 2200-0400$ h.LT. $n(H) \simeq 10^7$ cm^{-3}; $t = 0900$ h, $n(H) = 2 \cdot 10^6$ cm^{-3}; $t = 1100-2000$ h. LT, $n(H) \simeq 5 \cdot 10^5$ cm^{-3}), qualitatively agreeing with the daily variations of the temperature of the thermosphere.

***** T H E   E N D *****

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(*) NOTE from page 3 (infrapaginal)

When estimating the values of τ_1, τ_2, δ_2 the diffusion coefficients of H^+ ions in a gas of ions O^+ and through a neutral oxygenous atmosphere was respectively determined as [2] $D(H^+, O^+) \simeq 9.3 \cdot 10^7 T_i^{3/2}/n(O^+)$ and $D(H^+, O) \simeq 2.1 \cdot 10^{18} T^{1/2}/n(O)$, whereupon $D(H^+) = D(H^+, O^+) D(H^+, O)/[D(H^+, O^+) + D(H^+, O)]$. According to ionospheric estimates $k(H^+, O) \simeq 4.0 \cdot 10^{-10}$ cm$^3 \cdot$sec^{-1} [3]. According to data of laboratory measurements [4] at $T_i = T_i(O^+) = T_i(H^+) \simeq 1700$°K, $k(H^+, O) \simeq 7 \cdot 10^{-10}$ cm$^3 \cdot$sec^{-1}. The first value of $k(H^+, O)$ was admitted. The distribution of $n(h, O^+)$ was computed by the relative concentration of ions O^+ [5] and N(h)-profile at middle latitudes for 10 May 1963 at 1632 h. LT, obtained during external sounding of the ionosphere from AES "Alouette". Expression (6) was taken for the distribution of n(h, O).

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