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Aeronomy Branch

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ABSTRACT

The time dependent continuity equations for H^+ and O^+ are solved by means of a perturbation method. A solution for the diurnal variation of these ion species is presented to illustrate the dynamic effects of the coupling between F2-region and protonosphere. The variability of the ion composition transition level is discussed in view of the observed ion trough at high latitudes, and from this evidence is found for a continuous depletion of protons there.

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THE DYNAMIC COUPLING BETWEEN F2–REGION AND PROTONOSPHERE

INTRODUCTION

Hanson and Ortenburger (1961) were first to discuss the coupling, or more appropriate the lack of coupling between F2-region (where oxygen ions, O^+, are abundant) and protonosphere (where hydrogen ions, H^+, are dominant). They recognized the very significance of the diffusion barrier, H^+ encounters in collisions with O^+ when diffusing into and out of the protonosphere. This, and considering the fact that only a limited amount of protons is supplied through the charge exchange reactions

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

(which are the most significant chemical processes for H^+), Hanson and Ortenburger predicted that the characteristic time for refilling and depleting the protonosphere is in the order of a day and therefore one should expect insignificant diurnal variability of the ion content in the protonosphere.

As consequence of this inhibited and slow process of ionization exchange between F2-region and protonosphere, the assumption of steady state in describing these two regions (which would demand a short response time) is not valid. Their time dependence has to be considered as it affects the spatial structure of the ions.

Subject of this paper is to present a solution of the time dependent continuity equations for H^+ and O^+ in the topside ionosphere. A comparison between the steady state and time dependent solutions will allow to set criteria for the study of certain magnetospheric and ionospheric phenomena that are yet unresolved.

THEORY

Hanson and Patterson (1964) and Geisler (1967) have demonstrated that O^+ or H^+ distributions are only significantly affected by ion transport fluxes if these are in the vicinity of the critical fluxes. Critical fluxes are upper limits on ion fluxes that can be supported by chemical production and diffusion processes. For O^+ the critical flux is during day in the order of $5 \times 10^8/\text{cm}^2$ sec and thus significantly higher than that for H^+ which is close to the $10^8/\text{cm}^2$ sec (during minimum solar activity, Brinton et al. 1968). During nighttime however, the critical flux for H^+ may be comparable to that for O^+. The consequence is that dynamic variations in the protonosphere induce proton fluxes that, through a chain of chemical reactions also induce O^+ fluxes and they may affect the density of the oxygen ions. For this reason it may not be justified to treat the time dependent variation of the F2-region isolated without considering the protonosphere especially during nighttime.

Extensive theoretical work was done on the dynamic of the F2-region. Rüster (1967) solved the time dependent equations of motion and particle continuity to describe temporal fluctuations in the F2-region. Kritt (1967) solved the time dependent continuity equations and the quasi-stationary motion equations analytically to describe the diurnal variations of the O^+ concentration. Theoretical models of the F2-region have the advantage that they are linear because the ion concentration is several orders of magnitudes lower than the density of the neutral atmosphere which thus determines the diffusion coefficient. In the topside ionosphere, where the transition occurs into the protonosphere, the neutral atmosphere plays a minor role and the diffusion coefficients for O^+ and H^+ depend primarily on the concentrations of these two ion species. For this reason we deal with a nonlinear diffusion problem which is mathematically difficult to solve.

In the following it is assumed that the diurnal variation in the F2-region is known at 300 km and it is asked for the diurnal variation of O^+ and H^+ above this altitude. The continuity equations for the two ion constituents are

$$\frac{\partial [O^+]}{\partial t} = P_O - \frac{9}{8} R[H] \, [O^+] + R[H^+] \, [O] - B \frac{\partial}{\partial s} \left(\frac{[O^+] \, V_{O^+}}{B} \right) \tag{2}$$

$$\frac{\partial [H^+]}{\partial t} = P_H + \frac{9}{8} R[H] \, [O^+] - R[H^+] \, [O] - B \frac{\partial}{\partial s} \left(\frac{[H^+] \, V_{H^+}}{B} \right) \tag{3}$$

if diffusion along field lines (with distance s) is assumed to be dominant. It is

R charge exchange coefficient ($10^{-11} \, T^{1/2}$ cm^3/sec)

t time

V macroscopic transport velocity parallel to the magnetic field

The function B is proportional to the magnetic field

$$B = \frac{1}{r^3} (1 + 3 \sin^2 \lambda)^{1/2}$$

with

r geocentric distance

λ geomagnetic latitude

and accounts for the divergence of the magnetic field tubes. The first terms in (2) and (3) express the photoionization rates ($P_O \propto [O]$, $P_H \propto [H]$) the next two terms the charge exchange process (1) and the last terms stand for the transport process.

Adding Equations (2) and (3) leads after integration to

$$[H^+] V_{H^+} + [O^+] V_{O^+} = B \int_{s_e}^{s} \frac{ds}{B} \left(P_O + P_H - \frac{\partial [O^+]}{\partial t} - \frac{\partial [H^+]}{\partial t} \right) \equiv C(s, t); \qquad (4)$$

s_e is the field line distance to the equator. In Equation 4 some of the following boundary conditions

$$V_{H^+} = V_{O^+} = \frac{\partial [O^+]}{\partial s} = \frac{\partial [H^+]}{\partial s} = 0, \qquad \text{for} \qquad s = s_e \qquad (5)$$

were applied which lead to solutions that are symmetrical with respect to the equatorial plane and thus apply to equinox.

The linearized equations of motion are for ions

$$m_{O^+} [O^+] \frac{\partial V_{O^+}}{\partial t} + \theta_{H^+O^+} [H^+] [O^+] \left(V_{O^+} - V_{H^+} \right) + \theta_{O^+n} [O^+] N_n V_{O^+}$$

$$= - kT \frac{\partial [O^+]}{\partial s} + [O^+] m_{O^+} f + e [O^+] E \qquad (6)$$

$$m_{H^+}[H^+]\frac{\partial V_{H^+}}{\partial t}\theta_{H^+O^+}[H^+][O^+]\left(V_{H^+}-V_{O^+}\right)+\theta_{H^+n}[H^+]N_nV_{H^+}$$

$$=-kT\frac{\partial[H^+]}{\partial s}+[H^+]m_{H^+}f+e[H^+]E \qquad (7)$$

and for electrons

$$-kT\frac{\partial N_e}{\partial s}-eN_eE=0 \qquad (8)$$

where

N_n	neutral density
T	electron temperature, which is assumed to be equal to the ion temperature and to be constant with altitude.
f	acceleration parallel to the magnetic field due to gravitational and centripetal forces
E	electric polarization field parallel to the magnetic field
k	Boltzmann constant
m	mass
e	electric charge
N_e	electron density

The coefficients θ_{xy} are related to the diffusion coefficients D_{xy} according to

$$\theta_{xy}=\frac{kT}{([X]+[Y])D_{xy}}.$$

Estimations reveal that the time derivatives in Equations 6 and 7 are orders of magnitudes smaller than other terms, if diurnal variations are considered. Therefore the motion equations can be treated as quasi-stationary.

We eliminate the electric field by substituting Equation 8 into (6) which yields

$$\theta_{H^+O^+}[H^+][O^+]\left(V_{O^+} - V_{H^+}\right) + \theta_{O^+n}[O^+]N_n V_{O^+} = -kT\frac{\partial[O^+]}{\partial s} - kT\frac{[O^+]}{N_e}\frac{\partial N_e}{\partial s} + [O^+]m_{O^+}f \qquad (9)$$

Introducing (4) into (9) results in

$$[O^+]V_{O^+} = \frac{1}{\left(\theta_{H^+O^+}N_e + \theta_{O^+n}N_n\right)}\left\{kT\frac{\partial[O^+]}{\partial s} + kT\frac{[O^+]}{N_e}\frac{\partial N_e}{\partial s} + [O^+]\left(m_{O^+}f + \theta_{H^+O^+}C\right)\right\} \qquad (10)$$

In Equation (2) we substitute $V_{O^+}[O^+]$ through (10) and integrate it by applying condition (5). This leads to the integral differential equation

$$kT\frac{\partial[O^+]}{\partial s} + kT\frac{[O^+]}{N_e}\frac{\partial N_e}{\partial s} - m_{O^+}f[O^+] = -\theta_{H^+O^+}C[O^+] + \left(\theta_{H^+O^+}N_e + \theta_{O^+n}N_n\right)B\int_s^{s_e}\frac{ds}{B}\left(P_O - \frac{\partial[O^+]}{\partial t} - \frac{9}{8}R[H][O^+] + R[H^+][O]\right) \qquad (11)$$

and correspondingly for H^+ to

$$kT \frac{\partial [H^+]}{\partial s} + kT \frac{[H^+]}{N_e} \frac{\partial N_e}{\partial s} - m_{H^+} f [H^+] = \theta_{H^+O^+} C[H^+] + \left(\theta_{H^+O^+} N_e + \theta_{H^+n} N_n\right) B \int_s^{s_e} \frac{ds}{B} \left(P_H - \frac{\partial [H^+]}{\partial t} + \frac{9}{8} R[H][O^+] - R[H^+][O]\right) \quad (12)$$

Considering that $N_e = [O^+] + [H^+]$, the Equations (11) and (12) describe the temporal and spatial distributions (along field lines) for H^+, O^+ and N_e.

As boundary condition for integrating (11) and (12) we assume that at 300 km the temporal variation of O^+ is known and has the form

$$[O^+] = [O^+]_0 + [O^+]_1 \sin\left(\frac{2\pi}{\tau} t\right) \quad (13)$$

where τ is the period of one day. H^+ is assumed to be in chemical equilibrium through charge exchange and therefore is related to O^+, O and H by

$$[H^+] = \frac{9}{8} \frac{[O^+][H]}{[O]}$$

up to 400 km. O and H are assumed to be in diffusive equilibrium whereby their values vary at any altitude with the same period and phase as does O^+ (Equation 13). Also for T and T_n the same form of temporal variation is adopted.

SOLUTION PROCEDURE

The Equations (11) and (12) are solved by means of an iterative approximation in which the terms on the right hand side are treated as perturbations. For stationary conditions ($\partial/\partial t = 0$) this method was employed in (Mayr et al. (1967)), where it provided solutions accurate to 1% with computation times less than 10 sec on the IBM 360-75. We have therefore extended this method to solve the time dependent problem. This was accomplished by treating the time derivatives in (11) and (12) as perturbations which were applied iteratively in the following scheme.

With the k-th solution the time derivatives are assumed to be

$$\left(\frac{\partial [O^+]}{\partial t}\right)_k = \epsilon_k \left(\frac{\partial [O^+]}{\partial t}\right)_{k-1}$$

$$\left(\frac{\partial [H^+]}{\partial t}\right)_k = \epsilon_k \left(\frac{\partial [H^+]}{\partial t}\right)_{k-1}$$

where ϵ_k is a parameter that varies between

$$0 \leq \epsilon_{k-1} < \epsilon_k < \epsilon_{k+1} \leq 1$$

For the initial solution it is assumed that $\epsilon_1 = 0$ which is equivalent of assuming steady state. In subsequent solutions ϵ_k is slowly increased which means that we allow the time derivatives to become slowly effective. This assures the applicability of the perturbation method which demands small effects from the "perturbing" time gradient. A successive application of this procedure leads then to a convergence on the solution of the time dependent continuity equations when ϵ_k approaches 1.

RESULTS AND DISCUSSION

In the following, solutions are presented and discussed that were computed along a midlatitude field line that crosses 1000 km at 35°. Table 1 shows the time average (with subscript 0) and the amplitude (with subscript 1) for the input parameters. In Figures 1 through 3 the time dependent solutions for O^+, H^+ and N_e are shown in solid lines and for comparison the quasi-stationary solutions $(\partial/\partial t = 0)$ are shown in dashed lines.

Table 1

List of Input Parameters.

$[O^+]_{300}$ (cm^{-3})	$[O^+]_0 = 2.0 \times 10^5$	$[O^+]_1 = 5.0 \times 10^4$
$[O]_{500}$ (cm^{-3})	$[O]_0 = 1.5 \times 10^7$	$[O]_1 = 1.0 \times 10^7$
$[H]_{500}$ (cm^{-3})	$[H]_0 = 2.0 \times 10^5$	$[H]_1 = 2.0 \times 10^4$
T (°K)	$T_0 = 2.0 \times 10^3$	$T_1 = 5.0 \times 10^2$
T_n (°K)	$T_{n0} = 1.0 \times 10^3$	$T_{n1} = 2.0 \times 10^2$

As evident, the differences between time dependent and stationary solutions are significant and thus the assumption of steady state is not appropriate in describing the topside ionosphere. An interpretation of the various dynamic effects requires a thorough study of the complex interaction of the many physical quantities involved. As this is beyond the scope of this paper we shall confine ourselves to briefly discuss some of the major features.

The O^+ concentration exhibits at all altitudes a maximum during noon. The amplitude of its diurnial variation increases strongly with increasing altitude which is primarily the effect of the temporal variation in the plasma temperature. At lower altitudes, the differences between the stationary and time dependent solutions are negligible. At 700 km and above differences become apparent, first only during night at higher altitudes even during day. Differences of more than 30% and a negative phase shift are clearly evident at 1000 km.

The H^+ density shows a significantly more complex behavior. At 300 km its peak is in phase with that of O^+ and its minimum stretches over a rather long period of 8 hours during night. This results from the ion chemistry that involves variations of O^+, O and H. At 500 km, the temporal variation of H^+ shows an entirely different picture. A broad minimum is formed during day and a sharp maximum developes at night. The reason for this change can again be found in the ion chemistry which at this altitude involves significantly different $[O]/[H]$ ratios. In addition it is evident from the difference between the stationary and time dependent solutions that downward fluxes of H^+ enhance the proton concentration at night by almost a factor of two. At 700 km the temporal variations of H^+ result from the interaction of several processes. There the transition occurs from the F2-region into the protonosphere which means for H^+ that transport processes start to overrule chemical processes. This is apparent in the large differences between the stationary and time dependent solutions which show that during day upward fluxes decrease the proton density while at night downward fluxes enhance the H^+ concentration. These features prevail up to 2500 km where the H^+ density is decreased during day and enhanced at night, such, that the amplitude of the temporal variation decreases by a factor of two and the phase shifts by almost three hours.

The dynamic effects are clearest apparent in the electron density distribution (Figure 3). It shows that with increasing altitude the amplitude decreases while density minima and maxima shift in local time. These effects occur during night between 500 and 1000 km and during day between 700 and 2500 km, the reason being that the O^+-H^+ transition region is at night at a lower altitude than it is during day.

In Figure 4 the O^+-H^+ transition level is shown for the time dependent solution in solid line and for the steady state solution in dashed line. The difference is very pronounced, showing that dynamic effects enhance the transition level during day by 150 km and decrease it at night by 100 km. Thus the amplitude of the variation of the transition level increases as the result of dynamic effects. This feature may provide a simple qualitative criterion to test certain ionospheric and magnetospheric phenomena.

Ion composition measurements (Taylor et al. 1968) have shown that at high latitudes (> 50°) the mean ion mass at 1000 km is significantly higher than the value one should expect on theoretical grounds when assuming the ion composition to be in steady state (Mayr et al. 1967). This discrepancy can be interpreted as due to upward fluxes of protons that increase the mean ion mass and the O^+-H^+ transition level. As shown previously, during some period of the day such fluxes could result from the dynamic coupling between iononosphere and protonosphere. But, if this is the case then downward fluxes should prevail during some other period of the day and these fluxes would decrease transition level and mean ion mass below their steady state values. Taylor's mean ion mass observations were made during dawn and dusk periods and they do not show significant differences thus suggesting that the previously discussed dynamic effects may not be dominant. Unless a more detailed experimental coverage of the diurnal variation in the ion composition reveals that between dusk and dawn significant variations of m^+ and transition level exist at high latitudes, one has to postulate a continuous upward flow of protons. This would indicate that plasma is leaking across the magnetic field or escapes in open field tubes into the interplanetary space, mechanisms that were employed to explain the plasmapause and its relation to the ion composition at higher latitudes (Mayr 1968).

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FIGURE CAPTIONS

Figure 1 Computed temporal and spatial distribution of O^+. In solid lines the time dependent solution, in dashed lines the quasi-stationary solution $(\partial/\partial t = 0)$.

Figure 2 Computed temporal and spatial distribution of H^+. In solid lines the time dependent solution, in dashed lines the quasi-stationary solution.

Figure 3 Computed temporal and spatial distribution of N_e. In solid lines the time dependent solution, in dashed lines the quasi-stationary solution.

Figure 4 Computed temporal variation of the O^+-H^+ transition level. In solid line the time dependent solution, in dashed line the quasi-stationary solution.

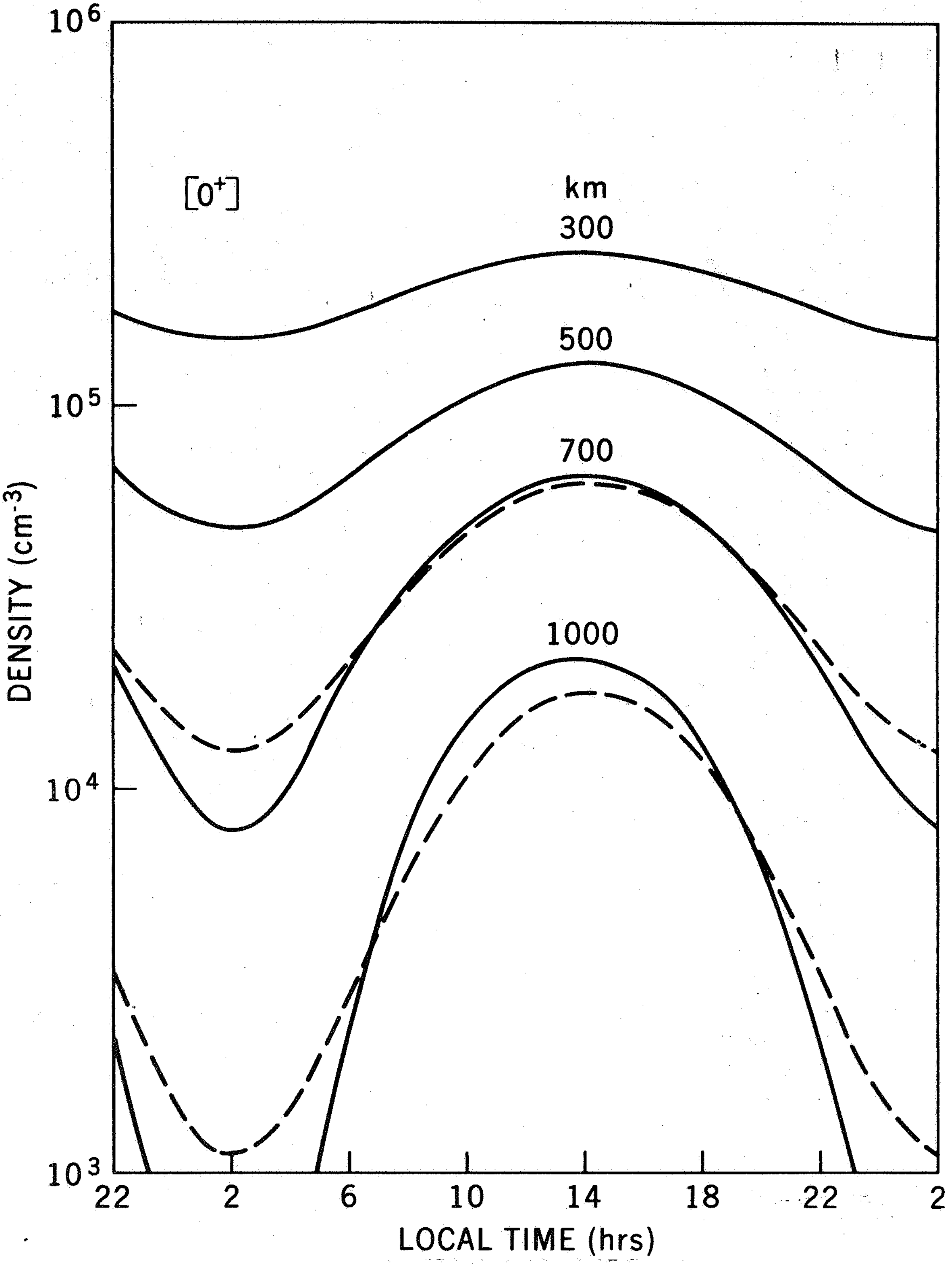

Figure 1. Computed temporal and spatial distribution of O^+. In solid lines the time dependent solution, in dashed lines the quasi-stationary solution ($\partial/\partial t = 0$).

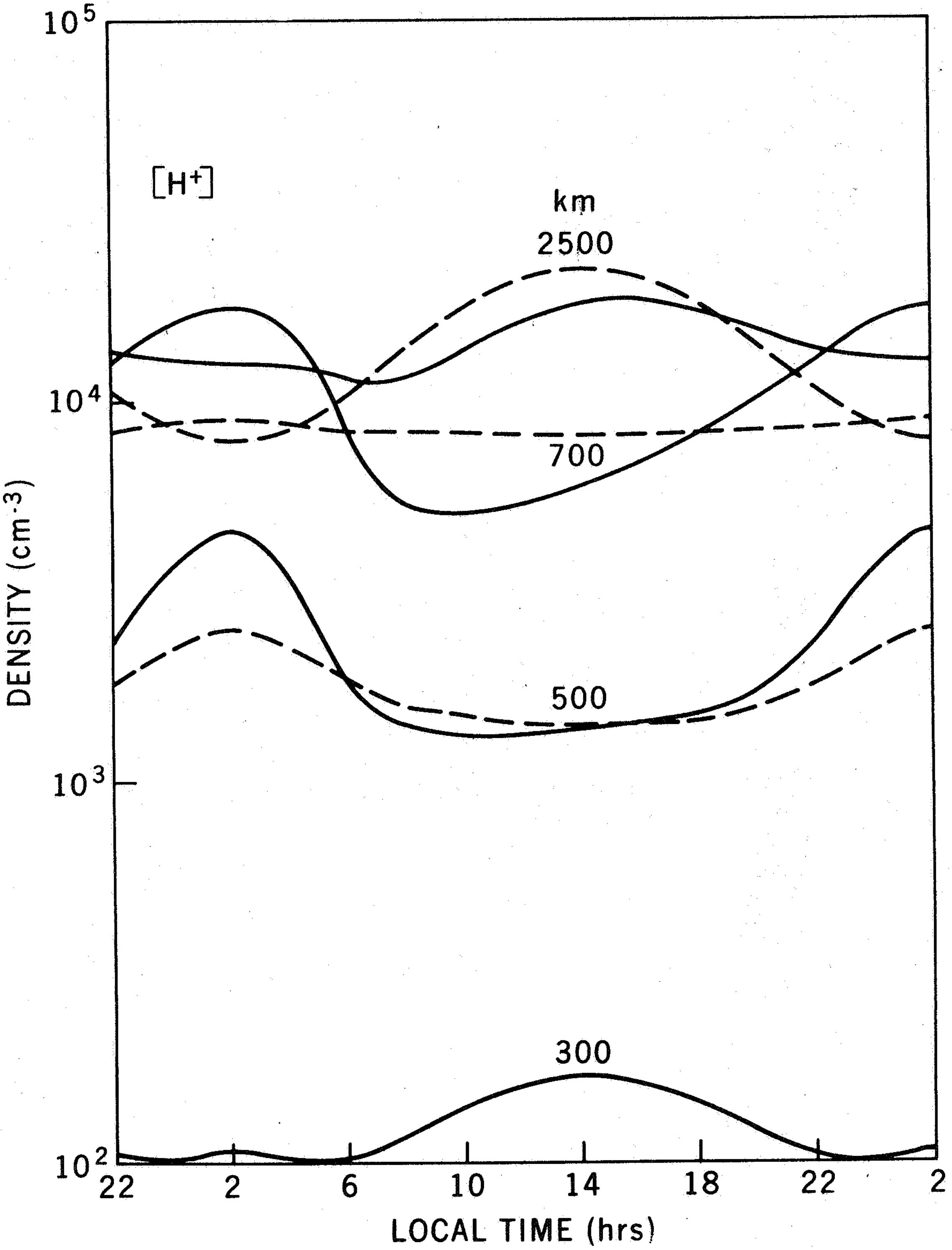

Figure 2. Computed temporal and spatial distribution of H^+. In solid lines the time dependent solution, in dashed lines the quasi-stationary solution.

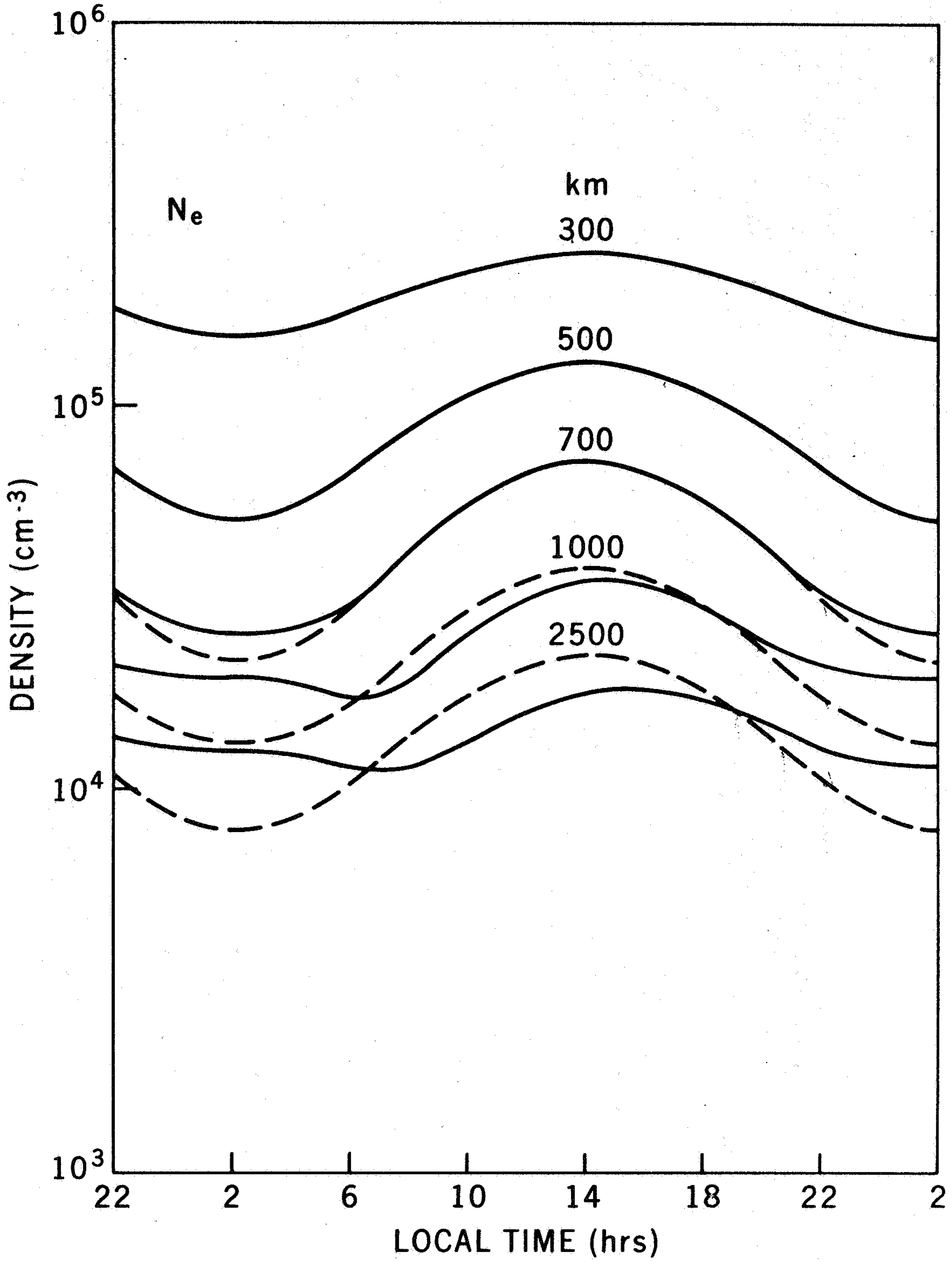

Figure 3. Computed temporal and spatial distribution of N_e. In solid lines, the time dependent solution, in dashed lines the quasi-stationary solution.

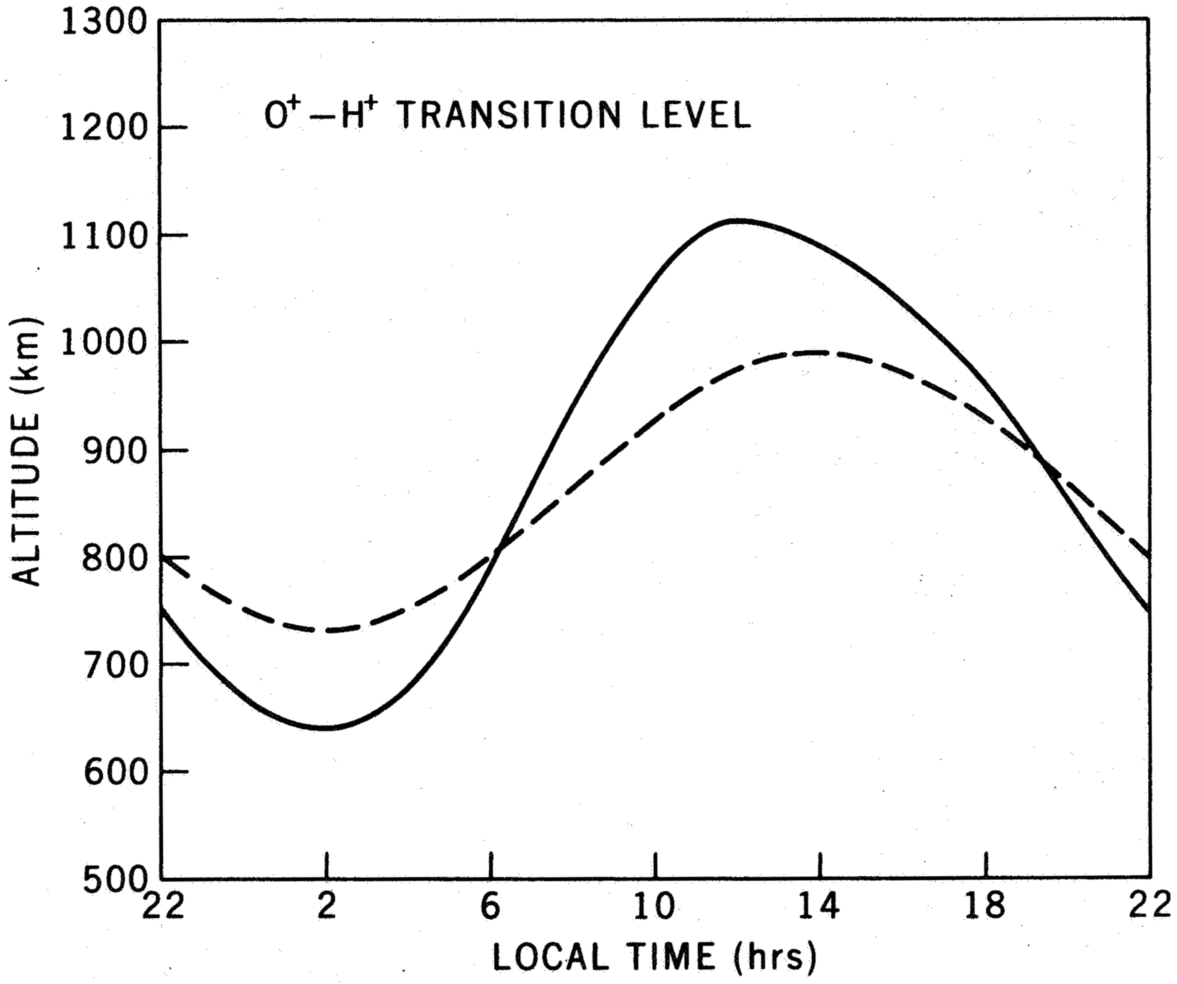

Figure 4. Computed temporal variation of the O$^+$-H$^+$ transition level. In solid line the time dependent solution, in dashed line the quasi-stationary solution.