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STUDY OF THE THERMAL PLASMA ON CLOSED FIELD LINES OUTSIDE THE PLASMASPHERE

H. G. MAYR
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ABSTRACT

Using OGO 4 ion composition measurements near the midlatitude light ion trough below 1000 kilometers, a model for the plasma state along the magnetic field lines is developed which produces, in the equatorial plane, the sharp density gradient characteristic of the plasmapause. In this model the field aligned plasmasphere boundary is a boundary across which the characteristics of the proton flux along the field lines change. Within the plasmasphere the proton fluxes along the field lines are of small or vanishing magnitude and may be directed either away from or towards the earth. By contrast, the small equatorial ion densities (~1/cc) known to exist on closed field lines outside the plasmasphere are consistent with the measured low altitude densities only if large proton fluxes, of the order of the critical flux, are directed along the field lines. These latter fluxes are directed away from the earth and correspond to the attainment of supersonic proton flow velocities on closed field lines outside the plasmasphere. This is consistent with the model of a supersonic polar wind convecting onto closed field lines.

CONTENTS

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INTRODUCTION

The existence of a sharp drop in the electron density (known as the knee or plasmapause) with increasing altitude near the equatorial plane at geocentric distances of a few earth radii is well established (e.g., Carpenter, 1963; Taylor et al., 1965). A change in the charged particle densities across the same group of field lines has also been observed at altitudes near 1000 kilometers in the form of troughs in the latitudinal distributions of the electrons and the light ions (Rycroft and Thomas, 1968; Taylor et al., 1968; Thomas and Andrews, 1968).

The model which best describes the origin of the plasmapause was originally developed by Nishida (1966). In this model the plasmapause is the boundary between magnetic field lines that are convected across the magnetospheric tail and field lines that are never transported to the tail. In the former group of field lines plasma escapes in the form of a supersonically flowing polar wind (Banks and Holzer, 1968) to interplanetary space when the field lines travel across the tail. Since the rate of replenishment from the ionosphere is low, the plasma densities on these field lines will be small compared to the densities on the latter group of field lines (which correspond to the plasmasphere) on which plasma escape is always prevented since the field lines are always closed. Implicit in this model is the existence of a continual motion of plasma directed away from the earth along the field lines in the depleted region outside of the plasmasphere. Using satellite ion ccmposition measurements this paper will explore some of the characteristics of these fluxes on field lines passing through the light ion trough.

THEORY

The region under discussion will be the magnetosphere above the F_2-peak, where O^+ and H^+ are the major constituents (Taylor et al., 1968). There O^+ is dominated entirely by transport processes. H^+ is chemically coupled to O^+ through charge exchange

$$O^+ + H \rightleftharpoons H^+ + O \qquad (1)$$

up to heights of typically 500 km; above this height transport processes also prevail for H^+.

Within the plasmasphere (typically $L < 4$) the plasma can be considered as confined in field tubes. The consequence is that transport processes are only induced through the diurnal redistribution of plasma causing proton fluxes into and out of the protonosphere. This is in contrast to the region outside the plasmasphere, where electromagnetic drift (Nishida, 1965) and possibly turbulent diffusion across the magnetic field (Mayr, 1968) may greatly affect the plasma distribution. Plasma drift out of the closed magnetospheric field lines results in a loss of plasma from the outer flux tubes. Ionospherically produced plasma moves upwards along the outer closed field lines to replenish the plasma loss (see Figure 1).

The characteristic time for filling up or depleting the magnetospheric density population may be of the order of a day or even longer at high latitudes where the field tubes are large. For this reason we deal also with a dynamic problem.

At present, a three-dimensional, time dependent theoretical model for the magnetosphere does not exist. Therefore, in discussing OGO 4 ion composition data, a semiphenomenological approach will be adopted in which the plasma distributions along field lines will be of prime concern.

The continuity equations for H^+ and O^+ are

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

and

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

with

s distance along a field line

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

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

with

r geocentric distance

λ geomagnetic latitude

and accounts for the divergence of the magnetic field tubes. The first term on the right hand side of (2) and on the right hand side of (3) represent the divergence of transport fluxes perpendicular to the magnetic field

$$P_H = - B_\perp \frac{\partial}{\partial s_\perp}\left(\frac{[H^+]\,V_{H^+\perp}}{B_\perp}\right) \tag{4}$$

$$P_O = -B_\perp \frac{\partial}{\partial s_\perp}\left(\frac{[O^+]\,V_{O^+}}{B_\perp}\right) \tag{5}$$

where $B_\perp$ is a fictitious field defined as orthogonal to the earth's magnetic field; $s_\perp$ being the field line distance.

Parallel to the magnetic field the equations of motion are

$$\left(m_{H^+}[H^+]\frac{\partial V_{H^+}}{\partial t}\right) + m_{H^+}[H^+]\,V_{H^+}\frac{\partial V_{H^+}}{\partial s}$$

$$+ \theta_{H^+O^+}[H^+]\,[O^+]\left(V_{H^+} - V_{O^+}\right) + \theta_{H^+N}[H^+]\,N_n V_{H^+}$$

$$= -kT\frac{\partial [H^+]}{\partial s} - kT\frac{[H^+]}{N_e}\frac{\partial N_e}{\partial s} - m_{H^+}g[H^+] \tag{6}$$

$$\left(m_{O^+}[O^+]\frac{\partial V_{O^+}}{\partial t}\right) + m_{O^+}[O^+]\,V_{O^+}\frac{\partial V_{O^+}}{\partial s}$$

$$+ \theta_{H^+O^+}[O^+]\,[H^+]\left(V_{O^+} - V_{H^+}\right) + \theta_{O^+N}[O^+]\,N_n V_{O^+}$$

$$= -kT\frac{\partial [O^+]}{\partial s} - kT\frac{[O^+]}{N_e}\frac{\partial N_e}{\partial s} - m_{O^+}g[O^+] \tag{7}$$

where

N_n neutral density

T plasma temperature $(T_e + T_i)/2$

g 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

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

If we assume that the transport velocity V_{H^+} is as high as the thermal velocity of the protons

$$V_{H^+} = \left(\frac{3\,kT}{m_{H^+}}\right)^{1/2}$$

and if we consider only diurnal variations, then we can estimate

$$\frac{\partial V_{H^+}}{\partial t} = \left(\frac{3\,kT}{m_{H^+}}\right)^{1/2} \frac{1}{24 \times 3600} \sim 12.5 \text{ cm sec}^{-1} \quad (\text{for } T = 5000°) \ .$$

The corresponding scale height for this acceleration thus becomes

$$\frac{kT}{m_{H^+} \dfrac{\partial V_{H^+}}{\partial t}} = 10^5 \text{ km}$$

which suggests that the first term in (6) and certainly also the one in (7) are negligible for the plasma distributions; therefore we shall neglect these terms as we indicate by putting them into parenthesis. By doing this we obviously must neglect any short term fluctuations or transient effects that may be associated with the formation of the plasmapause.

Perpendicular to the magnetic field plasma is transported due to pressure gradients causing diffusion and due to electric fields that produce plasma drifts with velocities

$$\vec{V}_{\perp} = \frac{\vec{E} \times \vec{B}}{B^2}$$

such plasma transport affects the particle balance and consequently the velocity distributions parallel to the magnetic field which can formally be derived by integrating Equations 2 and 3 to give for V_{H^+}

$$V_{H^+} = \frac{B}{B_e} \frac{[H^+]_e}{[H^+]} V_{H^+_0}$$

$$+ \frac{B}{[H^+]} \int_{s}^{s_e} \left(\frac{\partial [H^+]}{\partial t} - P_H - \frac{9}{8} R[H]\,[O^+] + R[H^+]\,[O] \right) \frac{ds}{B} \qquad (8)$$

For V_{O^+} the expression is similar. With the subscript e we refer to the equator. In the region where the magnetic field lines are closed, and it is assumed here that the plasmapause is within this region, the symmetry of the plasma population with respect to the equatorial plane requires that the transport velocities are zero at the equator:

$$V_{O^+_e} = V_{H^+_e} = 0 \qquad (9)$$

This is one set of boundary conditions to solve the continuity and motion equations along field lines.

Considering conditions (9) and the fact that charge transfer reactions are negligible in the protonosphere we find the important relation

$$V_{H^+} = \frac{B}{[H^+]} \int_s^{s_e} \left(\frac{\partial [H^+]}{\partial t} - P_H \right) \frac{ds}{B} \tag{10}$$

(for protonosphere) which will be discussed in the subsequent section.

The second set of boundary conditions is determined by the ion chemistry in the lower F_2 region which requires that O^+ and H^+ ions approach chemical equilibrium at lower altitudes. The F_2 region theory is complicated by atmospheric winds (Kohl and King 1965, Brace et al. 1969) and electric fields (Stubbe 1968), so to avoid the uncertainties inherent in these mechanisms we shall adopt for O^+ boundary values that are consistent with our observations. The requirement of chemical equilibrium (charge exchange) below 400 km will provide the boundary condition for H^+. The numerical procedure of solving the differential Equations (2), (3), (6) and (7) is basically described in Mayr et al. (1967).

DISCUSSION

Ion composition measurements made by the Bennett RF ion mass spectrometer on the polar orbiting satellite OGO 4 are used in this study. The selected measurements were made in the southern hemisphere on an August 8, 1967 pass and on an August 28, 1967 pass. The August 8 OGO 4 pass selected occurred at altitudes near 750 kilometers and at approximately 0550 LT, whereas the August 28, 1967 pass was made at altitudes near 900 kilometers at approximately 0430 LT. The characteristics of the ion spectrometer and of the OGO 4 orbits on these passes were described in detail by Grebowsky et al. (1969) who have observed that characteristic knees in the high altitude H^+ density distribution existed at the times of these OGO 4 measurements.

Diagram (2) reflects the state of the F_2-region revealing that the latitudinal variation in O^+ was relatively insignificant at 750 km where this ion species is the major constituent. Simultaneously, however, H^+ is found to decrease drastically toward higher latitudes with the trend to a recovery beyond $L = 6$. At higher altitudes this decrease in the H^+ density becomes even more pronounced (Figure 3); futhermore the O^+ concentration exhibits latitudinal variations that are almost opposite to the variations of H^+. These observations reflect apparently a significant increase of the O^+ - H^+ transition level with increasing latitude.

If one disregards dynamic effects in the ion composition H^+ can be assumed to be in charge exchange equilibrium almost up to the O^+ - H^+ transition level. Thus at this level the condition

$$\frac{8}{9}\frac{[H]}{[O]} \sim \frac{[H^+]}{[O^+]} = 1 \tag{11}$$

is nearly satisfied. This implies that the transition level is mainly determined by the neutral composition for which there is no evidence that it would significantly vary over the latitude range under consideration.

Based essentially on these arguments, previous investigations (Mayr et al. 1967) led to the conclusion that dynamic effects must be invoked to explain both the ion composition and plasmapause at high latitudes.

Our investigation will be concerned with a very narrow latitude range between 58° and 68° geomagnetic latitude; the corresponding L values are between 2.5 and 6. Consequently we shall adopt here a simplified ionosphere model in which we neglect latitudinal variations in the plasma density and temperatures of the F_2-region. In particular we assume

$$[O^+]_{400\ km} = 1.5 \times 10^5/cc$$

and

$$T_{e\,1000\ km} = T_{i\,1000\ km} = 2500\,°K$$

which is consistent with the measurements of Brace et al. 1966 regarding the electron temperature.

For the distributions of the plasma temperatures we adopted a quadratic form

$$T_e = T_0 + T_1(s - s_0) + T_2(s - s_0)^2$$

This distribution allows us to satisfy three conditions:

a. Zero temperature gradient at the equator,

b. $T_{e\,1000\ km} = 2500°K$, and

c. $T_e \approx T_g$ at low altitudes (300 km) where the plasma temperatures are expected to approach the gas temperature (due to the lack of a nighttime heat source).

For the neutral atmosphere we took a value of

$$[O]_{500\ km} = 1.3 \times 10^7/cc$$

corresponding to an exospheric gas temperature of

$$T_g = 1000°K$$

for 4.00 LT (Model 5 of CIRA 1965).

For atomic hydrogen we choose a value of

$$[H]_{500\ km} = 4 \times 10^5/cc\ ,$$

which corresponds to the value that was derived by Brinton et al. (1969).

With these inputs we attempted to reproduce

A. The measured ion composition at 900 km (Figure 3) and

B. The plasmapause with densities of typically 5/cc for L = 6 at the equator.

Figure 3 shows computed latitudinal distributions for O^+ and H^+ at 900 km compared with OGO 4 measurements. Under static conditions (that is without considerations of proton fluxes) the computed oxygen and hydrogen ion distributions are illustrated with triangle and X marks. In this case one can of course not expect significant latitudinal variations, which is, as pointed out before, in sharp contrast with observations. Figure 4 illustrates in X marks the corresponding equatorial distribution of the proton density. As we see H^+ decreases only by about a factor of three with the lowest value at about 10^2/cc, thus being almost two orders of magnitudes larger than the observed concentration.

Introducing fluxes, we adopted the following model:

At low latitudes ($L = 2.5$) electromagnetic drift and diffusion across the magnetic field in a non azimuthal direction, both induced by plasma escape at high latitudes, are ineffective. Consequently the proton velocity (Equation (10)) is determined by the local time variation in H^+, the latter we can expect to decrease during night due to the decreasing plasma temperature. Hence we adopt a downward flux at the base of the protonosphere and we adjust its value ($\sim 10^8$/cm^2 sec) such that we achieve agreement with the measurements.

At high latitudes where we are close to the region of plasma escape, where perpendicular diffusion and electromagnetic drift drain plasma out of the closed field tubes, these processes can more than compensate for the diurnal redistribution of plasma within the magnetosphere. Hence we can expect an upward flux of protons at the base of the protonosphere at $L = 6$. Its value we choose here such that the computed equatorial density agrees with the plasmapause observation of 5/cc.

At $L = 4$ between the two extremes we assume the flux to be zero.

The computed density distributions are shown in solid and dashed lines in Figure 4 at 900 km, and in Figure 5 for the equatorial plane. Figure 6 shows the altitude distributes of O^+ and H^+ for the three field lines $L = 2.5$, 4 and 6.

From these diagrams it is apparent that the basic features of the observations can be reproduced. At 900 km H^+ decreases rapidly toward higher latitudes while simultaneously O^+ increases with the tendency to produce a minimum in the total ion number density at L = 4. The opposite behavior in O^+ and H^+ is understandable. If we consider that the scale height of O^+ decreases by a factor of two as we proceed from the O^+ dominated F_2 layer into the protonosphere, then the increase of the O^+ - H^+ transition level with latitude must enhance the oxygen ion density at higher latitudes while it decreases the H^+ concentration. In the equatorial plane the computed proton concentration is shown to drop by more than two orders of magnitudes between L values of 2.5 and 6, which again is in basic agreement with plasmapause observations.

A discrepancy of major significance, however, becomes apparent when examining the H^+ densities at low altitudes for L = 6. At 900 km the computed H^+ concentration is only 3×10^1/cc, a value that is by more than a factor of ten lower than the observed hydrogen ion density. As evident in Figure 6 the scale height within the protonosphere is very large, thus in order to reproduce the low density at the plasmapause we had to start out with low proton concentrations within the ionosphere; in our model this is caused by a large drainage of protons.

For the calculations so far the nonlinear convection terms $V_{H^+}\,\partial V_{H^+}/\partial s$, $V_{O^+}\,\partial V_{O^+}/\partial s$ have been neglected in the motion Equations (6) and (7). And this implies that the protonosphere, in which H^+ - O^+ collisions are negligible, is in a state of fast diffusion which corresponds to diffusive equilibrium thus causing the large density scale height as discussed above.

Within the plasmasphere where we deal with proton densities between 10^3 - 10^4/cc, the upper limit of the proton velocities is in the range between 10^5 and 10^4 cm/sec assuming the critical proton flux to be in the order of $10^8/cm^2$ sec (Brinton et al. 1969). Such velocities are by about a factor of ten smaller than the thermal velocities of the protons ($\sim 10^6$ cm/sec) and this may justify the neglect of the convection terms. In the region of the plasmapause with proton densities between 10^2 and 5/cc the thermal velocities can be approached or even exceeded and thus we must consider this term in Equation (6); in fact we attribute the previously described discrepancy between our claculated and observed proton concentrations to the effectiveness of this convection term.

The convection term in Equation (6) is obviously positive definite with regard to the velocity direction and it is proportional to the spatial derivative of the velocity squared. A velocity increase with height decreases the scale height of the protons, a decrease of the velocity will increase the scale height. Hence, the requirements on the proton velocity distribution to match for L = 6 the relatively high proton concentrations at 900 km with the low densities near the plasmapause at the equator are the following:

1. Within the ionosphere and in particular within the O^+ diffusion barrier, the proton flux must be significantly lower than the critical flux so that drainage of protons will have a minor effect on the hydrogen ion density

at the O^+ - H^+ transition level. This implies that the proton velocity must be small at the base of the protonosphere.

2. Within the protonosphere the proton velocity has then to increase in order to reduce the proton scale height.

3. To satisfy the symmetry requirement with respect to the equatorial plane the proton velocity has to be zero at the equator. Strictly speaking this is only valid at equinox conditions. During solstice periods the zero velocity conditions will occur in either of the two hemispheres. Thus in any case we must expect that the velocity approaches zero at high altitudes which we assume here to be at the equator. This implies that the originally increasing proton velocity has to decrease toward the equator and thus forms a peak at some height. Above the peak, the effect of the convection term will be to increase the proton scale height.

Incorporating the convection term in our calculation, we adopted a velocity distribution that, consistent with the preceding specifications, allowed us to fit the ion composition measurements at 900 km with the equatorial plasmapause observations at L = 6. For this purpose we adopted quite arbitrarily, a Chapman function, which provides a reasonably good fit for a peak velocity of 3.6×10^6 cm/sec at 10,000 km (Figure 7 solid line). This velocity is considerably (more than twice) above the speed of sound. Also shown in Figure 6 is the resulting proton flux (dashed line).

Figure 8 presents the theoretical density distributions for L = 6. A comparison with ion composition measurements at 900 km reveals good agreement.

The equatorial proton density is evidently close to the plasmapause observation. The density increase above 10,000 km, results from the adopted decrease in the proton velocity that is required to satisfy the zero velocity condition at the equator. It is clear that the few available measurements do not allow a unique analysis of the velocity distribution, thus the detailed structure of the density recovery may be quite different from our model calculations. It is conceivable that in the equatorial region where essentially two plasma streams meet from both hemispheres, instabilities and shock conditions develop that cause structured and sharp density variations. To emphasize this uncertainty we showed the near equatorial density distribution dotted. For comparison we show also the ion composition, originally derived without considering the convection term (Figure 8 dashed lines).

In interpreting the first discussed proton velocity distribution, we have to consider Equation (10), which relates the proton flux to plasma loss across the field P_H and to temporal variations within the protonosphere $\partial [H^+]/\partial t$.

From Equation (10) it follows that drainage of plasma alone due to electromagnetic drift or diffusion ($P_H < 0$) would cause an increase of the plasma flow at least proportional to the converging cross sectional area of the field tube when going down to lower altitudes; that is

$$V_{H^+} [H^+] \propto \frac{1}{L^3} .$$

Our analysis (Figure 7) indicates this kind of increase, however only down to 2000 km. Below that height we require a significant decrease in the proton flux, which, according to Equation (10) can best be accounted for by a temporal decrease of the proton concentration.

CONCLUSIONS

The results of this study indicate that although charged particle fluxes may exist along any of the closed magnetic field lines they are of particular importance along field lines outside of the plasmasphere. In fact the plasmapause can be considered not only as a region of abrupt change in the H^+ density but also, equivalently (away from the equator), as a region of abrupt change in the magnitude of the H^+ flux directed along the field line. The plasmasphere is characterized by the existence of small or vanishing fluxes of charged particles which may be directed along the fields lines either toward or away from the earth. In contrast to this behavior, field aligned H^+ fluxes outside the plasmasphere are large (i.e., of the order of the critical flux) and directed away from the earth.

On field lines which pass through the light ion troughs observed by OGO 4, the field aligned H^+ flow must attain supersonic velocities in order that the model computations yield densities near the equatorial plane comparable to those observed experimentally. (Because of these large flow velocities, the nonlinear term $v\, \partial v/\partial s$ dominates the physics of the plasma distribution outside the plasmasphere at high altitudes.) Such supersonic velocities may result from the convection of the supersonically flowing polar wind ions (Banks and Holzer, 1968) onto the closed field lines.

Along the trough field lines, the H^+ density may not continually decrease with altitude above the O^+ - H^+ transition level. Beginning at the O^+ - H^+ transition altitude, the computed H^+ density initially decreased with altitude, but it eventually recovered and became a relative maximum at the equator. How large the recovery of the H^+ density is near the equator and the location at which the recovery begins depends upon the functional form of the H^+ flow velocity along the field line which in turn is dependent upon whether the transition from supersonic to subsonic flow occurs continuously, as assumed, or discontinuously across a collisionless plasma shock. More extensive measurements, than presently exist, of ion composition and charged particle fluxes along closed field lines outside the plasmasphere are required to accurately determine the ion velocity profiles along these field lines and to determine whether supersonic ion flow velocities are indeed present on these closed lines of force.

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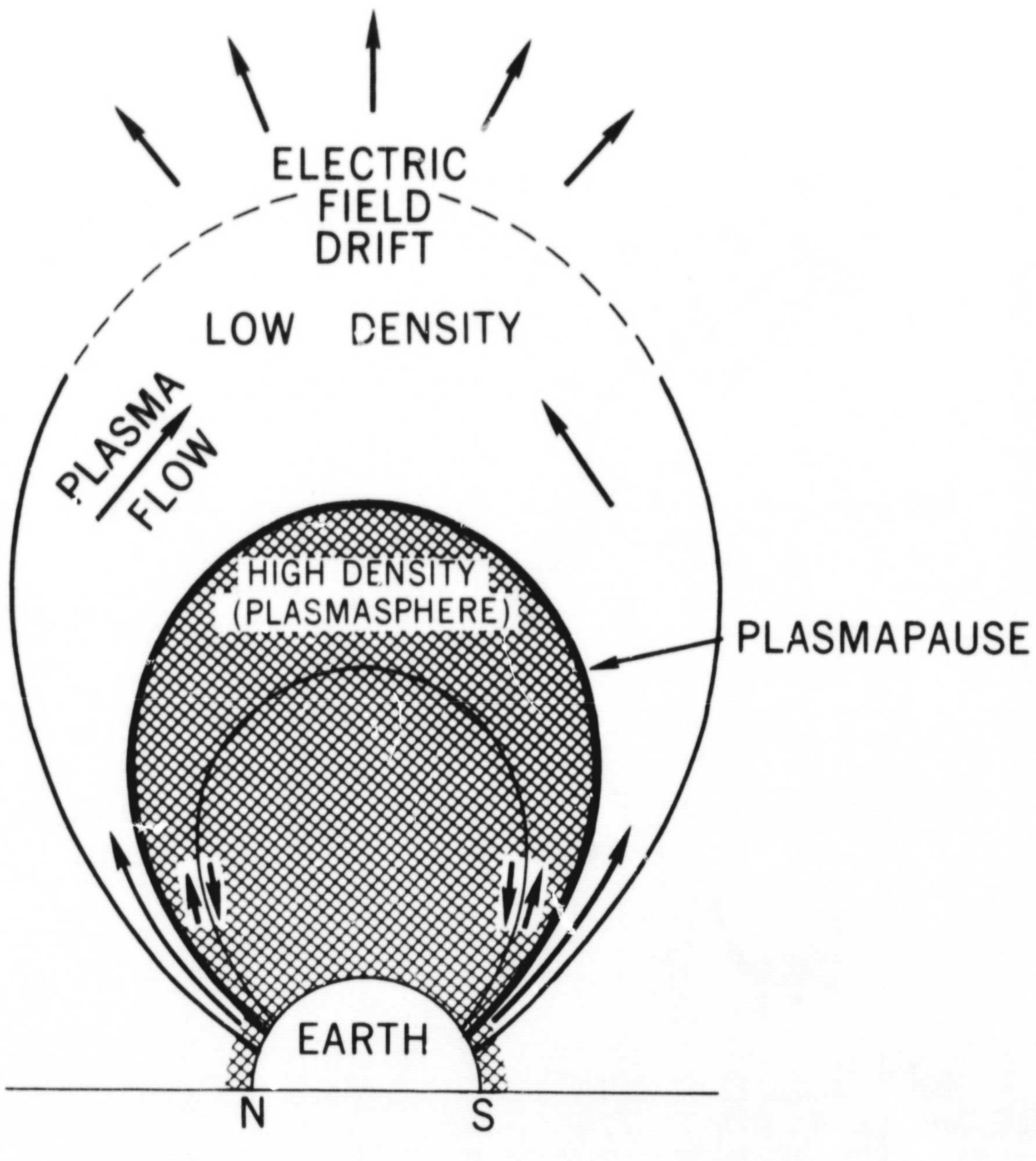

Figure 1. Schematic model of the mechanism that produces the plasma flow along the closed field lines. Plasma is lost due to electric field drift onto open field lines. Ionospherically produced plasma moves upward along the closed field lines to replenish this plasma loss.

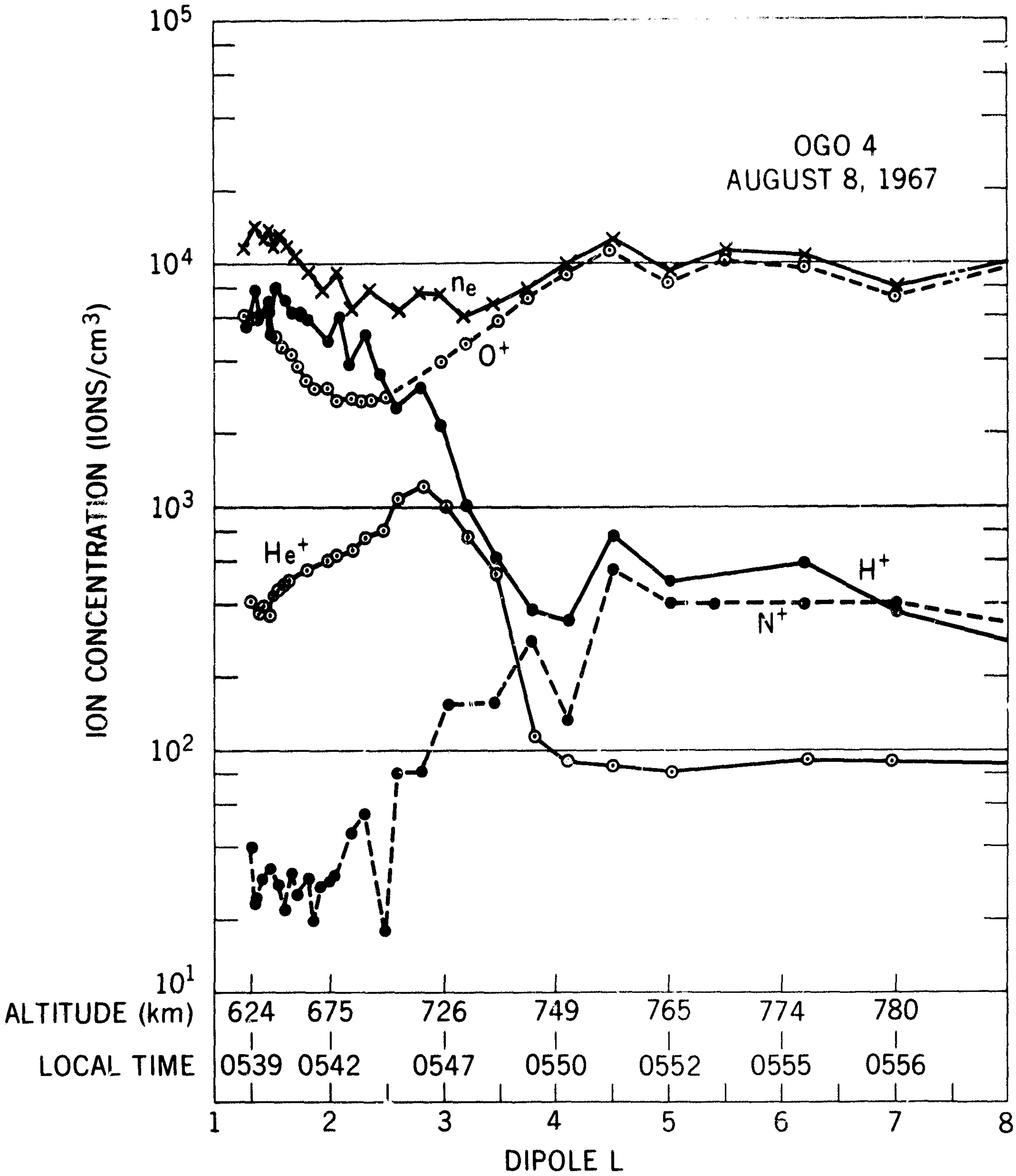

Figure 2. OGO 4 Ion Composition Measurements – August 8, 1967 (from Grebowsky et al., 1969)

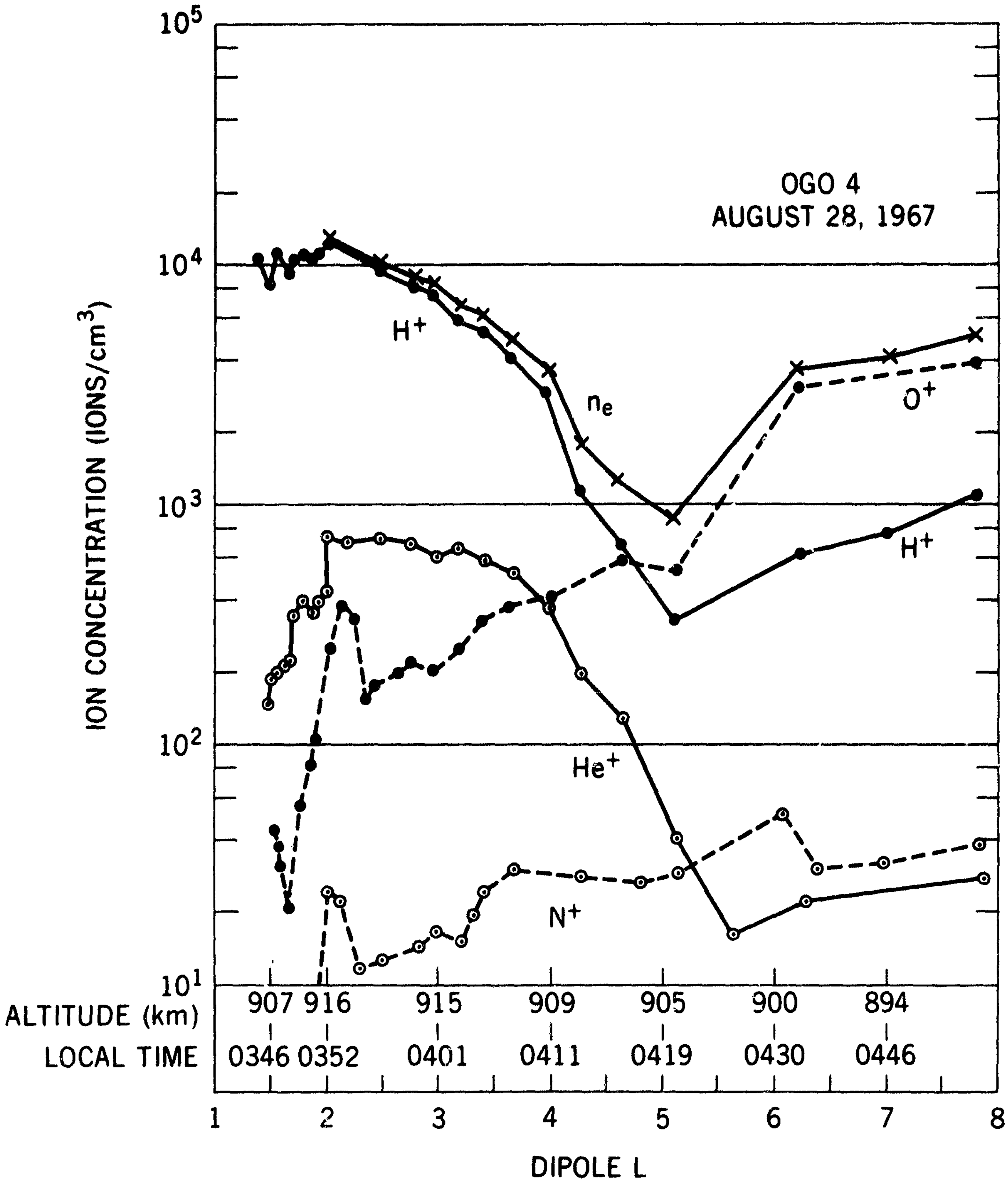

Figure 3. OGO 4 Ion Composition Measurements – August 28, 1967 (from Grebowsky et al., 1969)

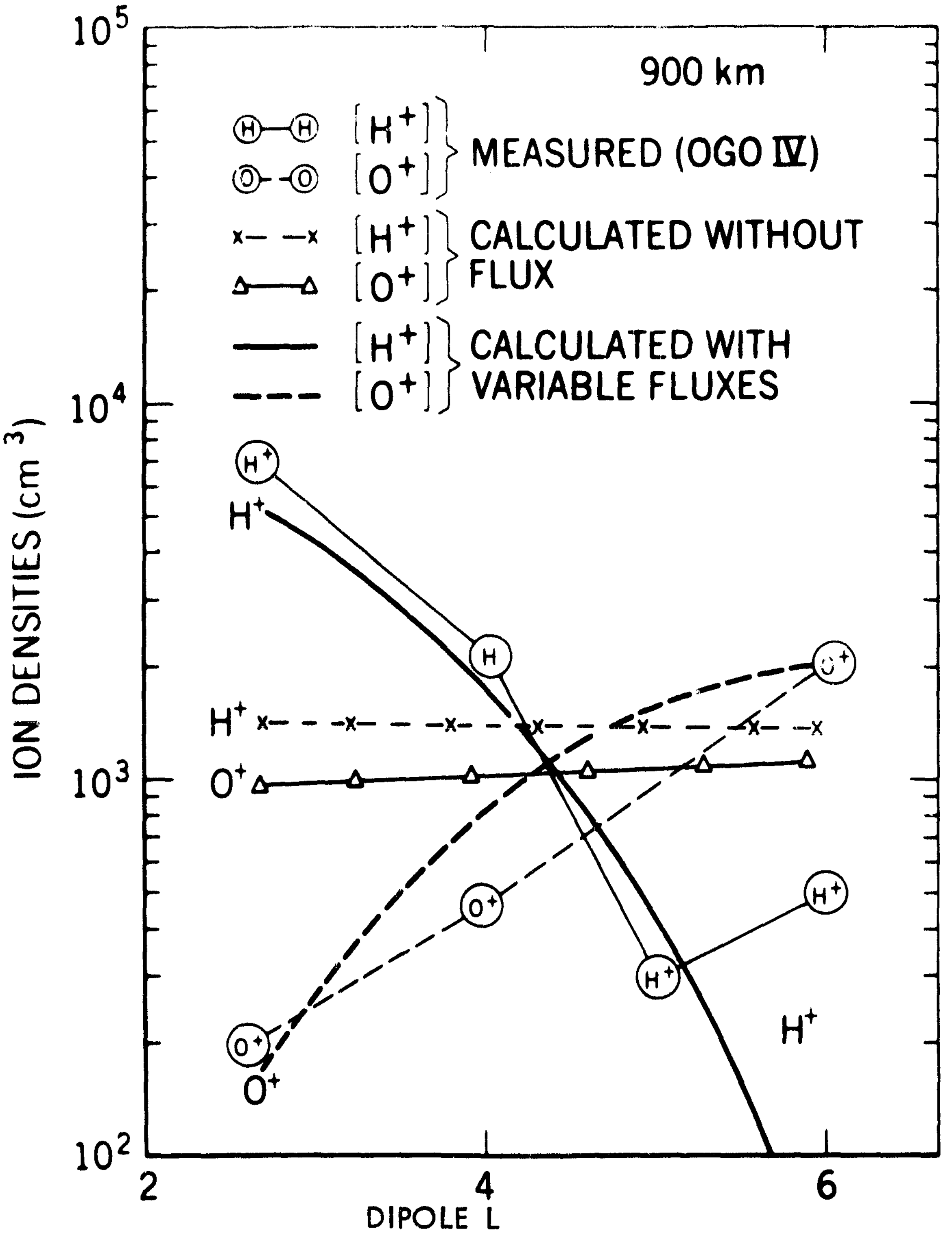

Figure 4. Comparison Between Measured and Computed Ion Composition at 900 km.

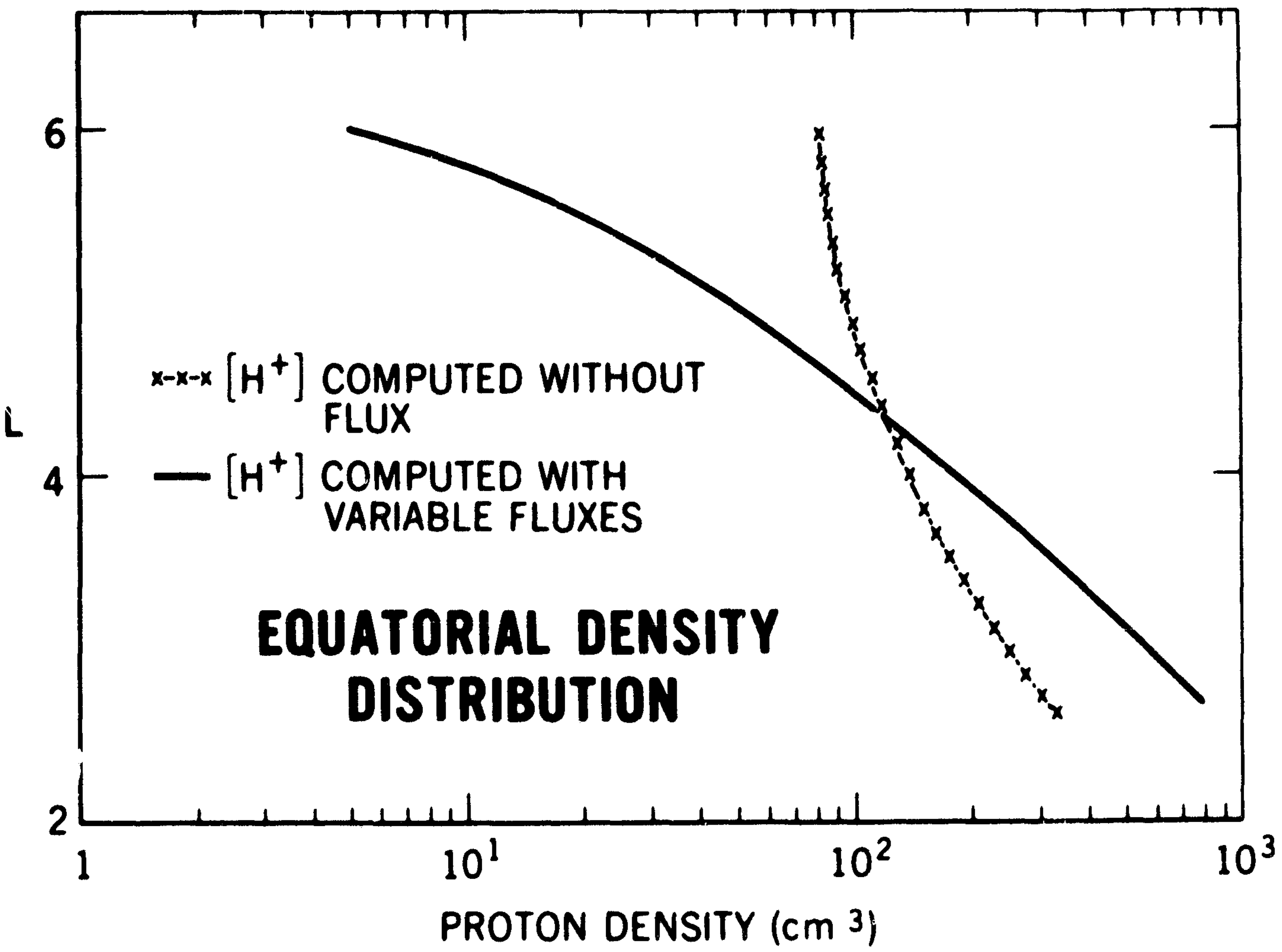

Figure 5. Computed Proton Distribution in the Equatorial Plane

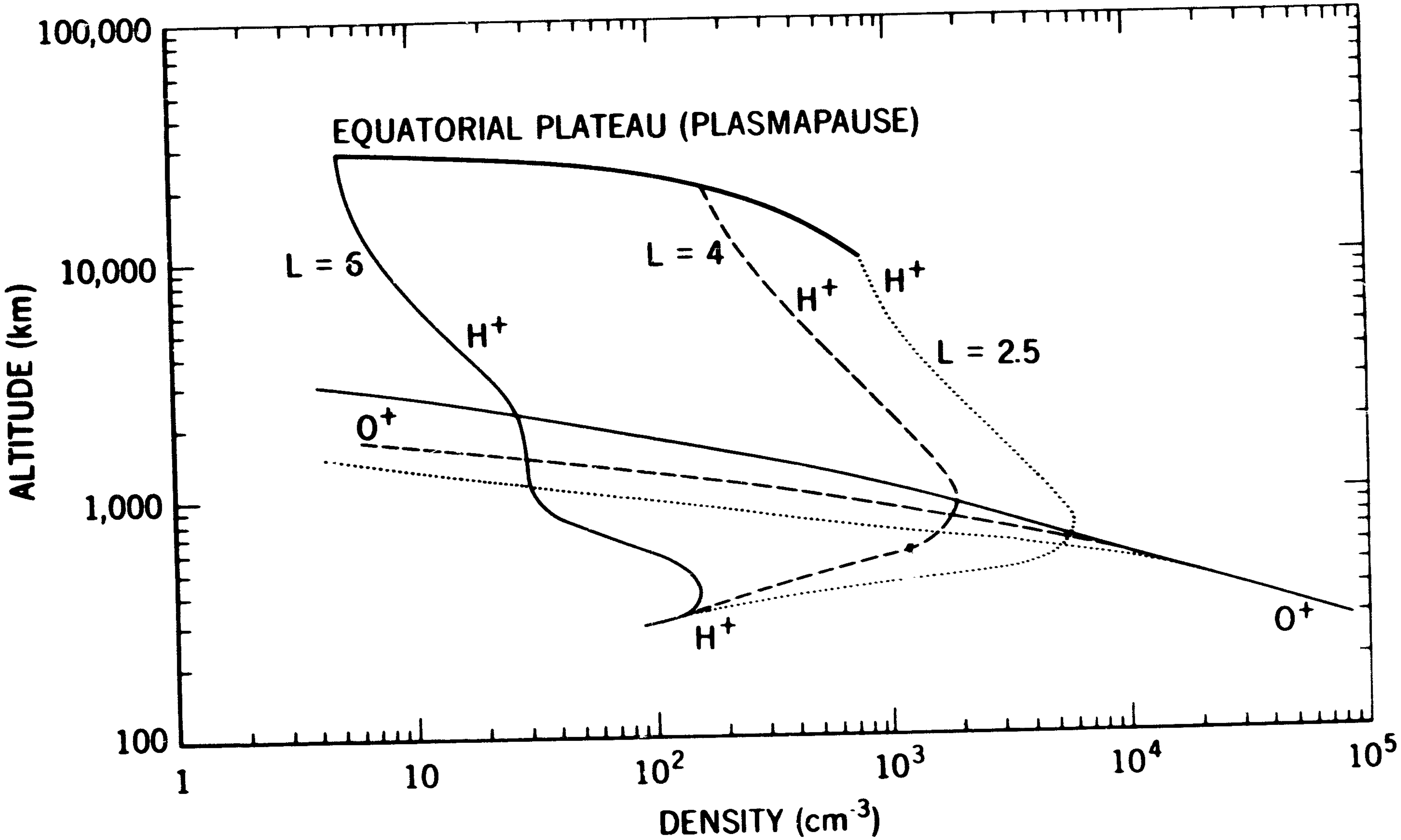

Figure 6. Computed ion distribution along three field lines. A downward flux was assumed at L = 2.5, an upward flux was assumed at L = 6 and static equilibrium was assumed at L = 4. Note that the plasmapause is reproduced.

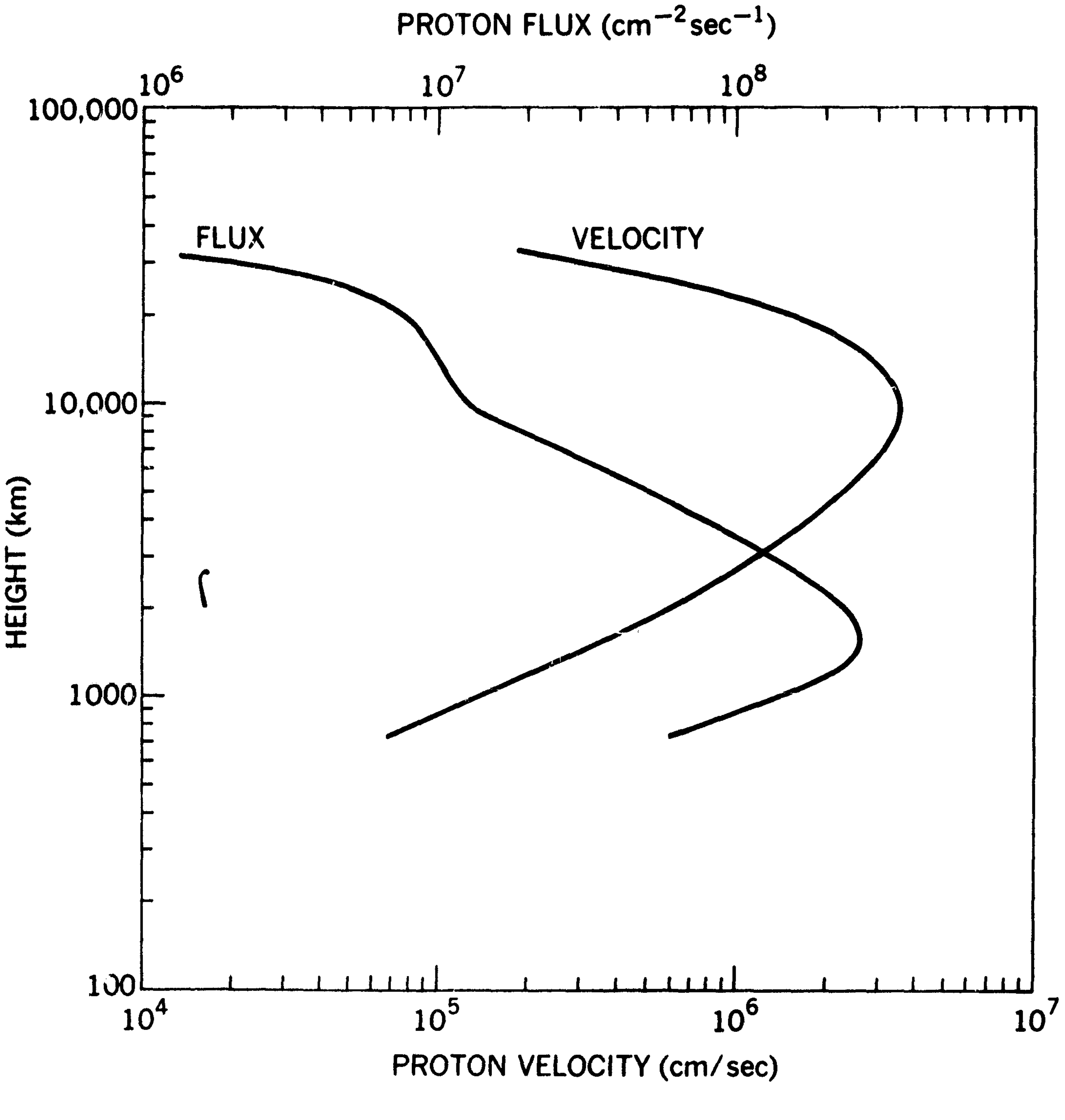

Figure 7. Assumed velocity and flux distribution which serve to reproduce both the ion composition at 900 km and the plasmapause density at L = 6.

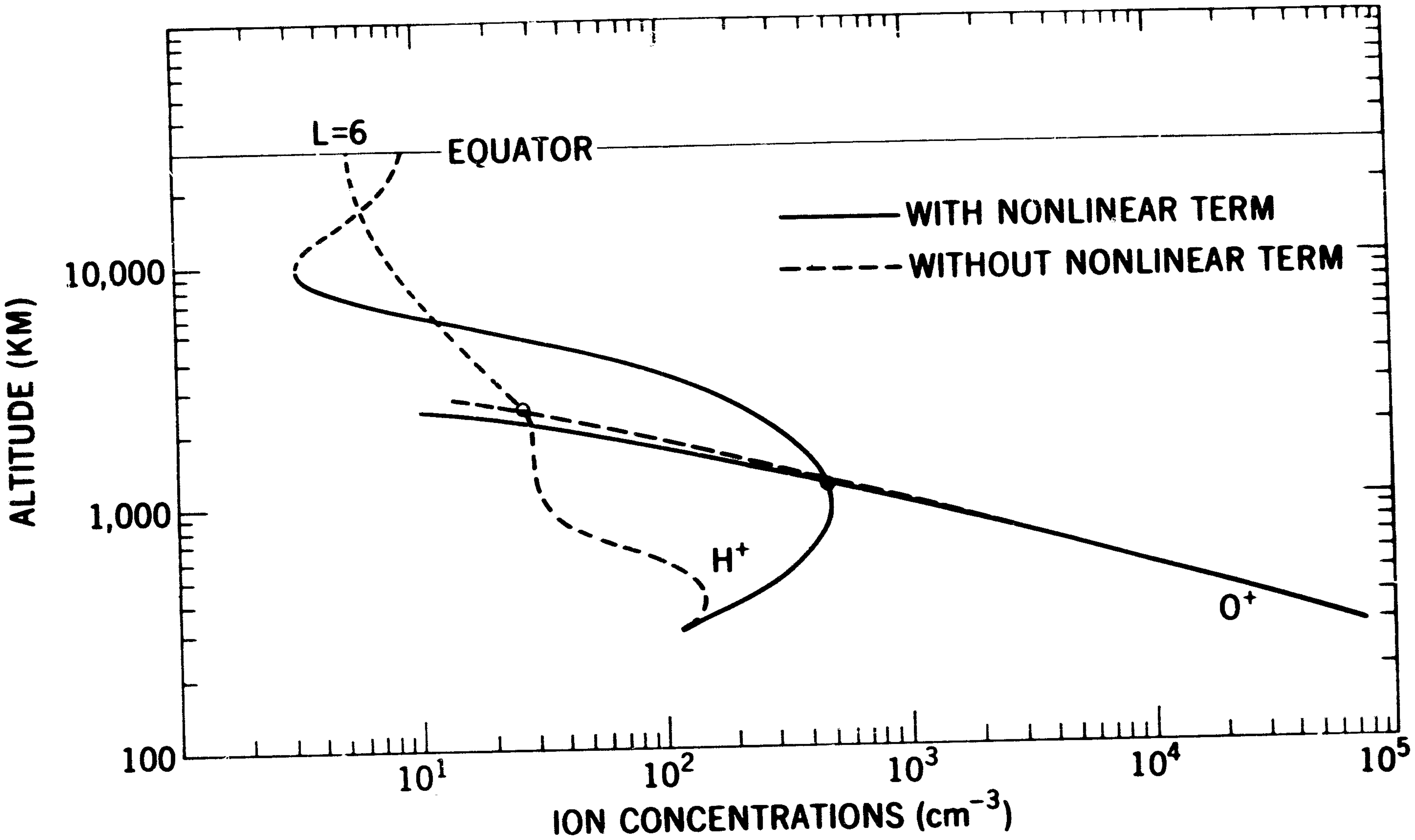

Figure 8. Computed ion compositions with consideration of convection term for the velocity distribution that is shown in Figure 7 (solid line) and without the convection term but with an upward flux at ionospheric levels (dashed line).