X-621-70-311

PREPRINT

NASA TM X- 65328

ALTITUDE VARIATION OF ION COMPOSITION IN THE MIDLATITUDE TROUGH REGION; EVIDENCE FOR UPWARD PLASMA FLOW

HENRY C. BRINTON
JOSEPH M. GREBOWSKY
HANS G. MAYR

AUGUST 1970

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

X-621-70-311
PREPRINT

ALTITUDE VARIATION OF ION COMPOSITION IN THE MIDLATITUDE TROUGH REGION; EVIDENCE FOR UPWARD PLASMA FLOW

by

Henry C. Brinton, Joseph M. Grebowsky, and Hans G. Mayr

Laboratory for Planetary Atmospheres

August 1970

GODDARD SPACE FLIGHT CENTER

Greenbelt, Maryland

ALTITUDE VARIATION OF ION COMPOSITION IN THE MIDLATITUDE TROUGH REGION; EVIDENCE FOR UPWARD PLASMA FLOW

By

Henry C. Brinton, Joseph M. Grebowsky, and Hans G. Mayr

Laboratory for Planetary Atmospheres

ABSTRACT

Midday ion composition measurements made by the Explorer 32 ion mass spectrometer in the midlatitude trough region (L = 5.0 - 10.5) are compared with measurements made within the plasmasphere (L=1.8 - 2.2). In the trough the light ion (H^+ and He^+) concentrations are observed to decrease with altitude between 600 and 2500 km—a region in which O^+ is the major ion. Within the plasmasphere, however, the concentrations of the light ions, when minor, increase with altitude. Model calculations indicate that the behavior of the plasmasphere profiles is consistent with a state of stationary diffusive equilibrium, whereas a dynamic plasma state is required to account for the trough distributions. Upward directed H^+ fluxes having near sonic speeds above 2000 km are required to reproduce the measured trough variations. This 'trough wind', consisting of a rapid upward flow of H^+, can be interpreted as evidence for the convection of the supersonic polar wind onto closed trough field lines.

CONTENTS

INTRODUCTION

Although the loss of light ions from the polar ionosphere has for several years been the subject of theoretical consideration, only limited observational evidence for an upward flow of plasma has thus far been reported. Axford (1968) recognized the supersonic nature of the flow and suggested the name 'polar wind'; a full development of the theory of the wind was subsequently presented in a series of papers by Banks and Holzer (1968, 1969 a, b, c).

The first detailed experimental study of the latitudinal variation of ion composition was made with the ion spectrometer on OGO 2. This investigation, reported by Taylor et al. (1968), revealed a persistent depletion of H^+ and He^+ above 60° geomagnetic latitude, forming a trough in the light ion concentration. The light ion trough was subsequently observed with the ion spectrometers on Explorer 31 (Hoffman, 1969), Explorer 32 (Brinton et al., 1969), OGO 4 (Taylor et al., 1970), OGO 6 (Taylor, 1970a), and the OGO 4 retarding potential analyzer (Chandra et al., 1970). This depletion of ionization was first related to an upward loss of plasma at the poles by Nishida (1966), and was more recently interpreted by Mayr et al. (1970) as evidence for a fast-moving upward flux of H^+ ions along the trough field lines. Hoffman (1969) has reported the first direct observation of upward streaming H^+ ions at polar latitudes; he interprets the relative displacement of H^+ and O^+ current peaks in his Explorer 31 ion spectrometer data as evidence that H^+ ions are flowing upward with a velocity of 10-15 km/sec at 2800 km altitude.

In this paper, altitude profiles of thermal O^+, N^+, H^+ and He^+, derived from Explorer 32 ion mass spectrometer measurements in the trough region between 58° and 71° geomagnetic latitude, are presented. These distributions, which were obtained in the altitude range 500-2500 km, are compared with corresponding profiles measured inside the plasmasphere (28° - 44° geomagnetic latitude). An observed decrease in the H^+ and He^+ concentrations with increasing altitude in the trough is interpreted as evidence for an upward flow of plasma along closed trough field lines. The form of the altitude profiles indicates that the H^+ flow approaches the ion thermal speed. These observations of plasma flow along trough field lines provide evidence for the existence of a 'trough wind' which is consistent with the convection of the polar wind onto closed field lines as was hypothesized by Axford (1969) and Mayr et al. (1970). In contrast to the trough observations, ion altitude profiles measured on field lines inside the plasmasphere reveal an increase in H^+ concentration with increasing altitude when O^+ is the major ion, as would be expected under conditions of stationary diffusive equilibrium.

THE EXPERIMENT

The Explorer 32 satellite, which was operable from May 1966 to March 1967, carried a complement of aeronomy instruments including a Bennett RF ion mass spectrometer designed to measure the concentrations of thermal positive ions in the mass range 12 to 19 amu and 1 and 4 amu. The satellite orbit, with an inclination of 64.7°, had a perigee of 277 km and an apogee of 2725 km. A detailed description of the instrumentation, the orbit, and data reduction techniques was presented by Brinton et al. (1969).

DATA COVERAGE AND SELECTION

Times and locations of measurements

The four black regions in Figure 1 indicate, with respect to the earth's magnetic field, the locations of the ion composition measurements to be discussed in this paper. All of the reported measurements were made on the day side of the earth, within three hours of local noon, and within a restricted range of latitude and longitude. The trough measurements, extending from approximately 500 to 2500 km altitude, were made in the region from L = 5.0 to 10.5 (58° to 71° and -58° to -71° geomagnetic latitude). The measurements inside the plasmasphere, extending from approximately 800 to 2700 km, were made in the L range between 1.8 and 2.2 (28° to 44° and -28° to -44° geomagnetic latitude).

The shaded areas in Figure 2 indicate the restricted latitude and longitude extent of the data to be discussed. Only measurements made in the geomagnetic longitude intervals 60° to 120° and -60° to -120° are included in the data sample, since in these regions geographic season and 'magnetic season' are the same (the geographic and geomagnetic equators cross at ±90° geomagnetic longitude). The importance of considering both geographic and magnetic season in the study of ion composition data has been demonstrated in earlier reports on the Explorer 32 (Brinton et al., 1969; Brinton et al., 1970) and OGO 4 (Taylor et al., 1970; Taylor, 1970b) spectrometer measurements.

The chosen time intervals for the O^+, N^+, and H^+ data presented here were sixty-day periods centered on June 22, 1966, September 22, 1966, and December

22, 1966 (a thirty-day period was used for He^+ because of its strong seasonal variation). We have thus obtained, for northern and southern hemispheres, altitude profiles of ion composition under summer, equinox, and winter conditions. Northern and southern hemisphere data obtained during the same magnetic season have been combined in order to extend the altitude range of the profiles.

Magnetic activity effects

In plotting the ion concentration altitude profiles it was found that scatter in the distributions could be reduced by eliminating data obtained on days of strong magnetic disturbance. On such days the concentrations of O^+ and N^+ in the altitude range 500-1500 km were found to be a factor of 1.5-2.5 higher than on undisturbed days, an effect which may be attributable to increased ion temperature (Bauer and Krishnamurthy, 1968). Deviations of comparable magnitude were observed in the H^+ and He^+ concentrations. To reduce the scatter related to magnetic activity, data obtained on days for which $Ap \geqslant 22$ ($Kp = 4-$) have been omitted from the ion distributions. For the O^+ points near 2500 km it was necessary to be even more restrictive: excessive spread in these data was eliminated by placing an upper limit on the magnetic activity of $Ap = 9$ ($Kp = 2+$).

RESULTS AND INTERPRETATION

Altitude profiles of ion concentrations

Altitude distributions of the primary atmospheric ions detected in the trough under daytime equinox and winter conditions are shown in Figures 3 and 4, respectively; corresponding profiles of O^+ and H^+ measured within the plasmasphere at equinox are depicted in Figure 5. Since the observed altitude variation of the light ion concentrations along trough field lines (Figures 3 and 4) differs noticeably from the variation along plasmasphere field lines (Figure 5), model studies have been conducted to determine what differences between the plasma states in these regions could account for this behavior. Diffusive equilibrium profiles have been calculated for the primary ionic constituents in each region, and these model distributions are included in the figures for comparison with the observed variations.

Trough data and diffusive equilibrium models

The equinox trough measurements (Figure 3) reveal a decrease in concentration with increasing altitude of all four constituents, including the light ions H^+ and He^+. Similar distributions are observed in the trough during winter (Figure 4), the light ion concentrations again decreasing with altitude. It should be noted that the winter measurements extend to 2500 km, considerably higher than the range of the equinox data. (The winter N^+ profile is parallel to that of O^+; because it partially overlaps the H^+ data it has been omitted from the figure for clarity.)

By comparing the observed H^+ and He^+ distributions with the computed model profiles in Figures 3 and 4 it may readily be seen that the concentration variations measured on trough field lines do not correspond to a stationary state of diffusive equilibrium. The model profiles were calculated upward from observed base concentrations at 700 km (Figure 3) and 900 km (Figure 4) assuming a common ion-electron temperature of 2500° K—a typical value near 1000 km altitude in the trough region (Miller, 1970)—and using the expressions for the variation of ion concentration in an isothermal diffusive equilibrium state as developed by Angerami and Thomas (1964). While the observed profiles of O^+ and N^+ have been reproduced, the variations of H^+ and He^+ are not in agreement with the model profiles. As shown in Figures 3 and 4, the stationary diffusive equilibrium model requires that the concentrations of the light ions increase with altitude when O^+ is the major ion. The measured profiles, in contrast, are characterized by H^+ and He^+ concentrations which decrease with altitude throughout the altitude range of the measurements, even though they were minor constituents. Hence, a stationary state of isothermal diffusive equilibrium apparently does not exist along trough field lines. We shall return to a consideration of the plasma state in the trough in a later section.

Plasmasphere data and diffusive equilibrium model

Measurements of O^+ and H^+ concentrations made inside the plasmasphere under daytime equinox conditions are shown in Figure 5. The N^+ profile parallels the O^+ distribution and has been omitted. An insufficient number of points were available to define the altitude distribution of He^+, and it too is not shown. In sharp contrast with the behavior of the light ions in the trough region, the concentration of H^+ in the plasmasphere (Figure 5) is observed to increase with altitude, in agreement with a stationary diffusive equilibrium model.

For the plasmasphere case, in order to produce model profiles which match the measured O^+ and H^+ concentrations, the existence of temperature variations along the field lines and consequent thermal diffusion were invoked. Experimental results (Mahajan and Brace, 1969; Sanatani and Hanson, 1970) indicate, in fact, the existence of upward directed electron and ion temperature gradients near 1000 km with magnitudes of a few degrees K/km. In our study the solution of the steady state heat conduction equation without local heating or cooling was used for the electron temperature variation along the field line. Allowing for a difference between the ion and electron temperatures, the ion temperature was assumed to exponentially approach the electron temperature with increasing altitude (Schunk and Walker, 1969). The actual temperature profiles used in the plasmasphere model computations are depicted in Figure 6.

The theoretical O^+ and H^+ distributions in Figure 5 were generated using the equations of thermal diffusion (Walker, 1967; Schunk and Walker, 1969) in conjunction with the temperature variations of Figure 6; they are seen to agree favorably with the measured concentrations, thus indicating that the plasmasphere ion distributions can be accounted for by a stationary state model. (It should be noted that an attempt was also made to fit the trough data to a stationary state model assuming upward directed temperature gradients and using the thermal diffusion equations. No realistic temperature variation could be found, however, which could account for the measured trough distributions.)

Transition region data (L = 2.2 - 5.0)

The variation with altitude of H^+ ion concentration under daytime equinox conditions has been studied throughout the range L = 1.8 - 12.0. Figures 3 and

5 depict the observed H^+ behavior near the extremes of this range. At L values between those selected for the figures the H^+ distribution undergoes a transition from its observed plasmasphere form (increasing concentration with altitude) to its trough characteristic (decreasing concentration with altitude). It appears that the crossover in this behavior occurs in the L range 3.0 - 3.9; the H^+ data in this interval was sufficiently scattered that it was not possible to define an altitude profile of the concentration.

Flux model studies

Having seen that the ion distributions measured in the trough region cannot be reproduced by a stationary state plasma model, a study has been made to determine whether a net flow of plasma along the trough field lines could account for the observed profiles. If the behavior of the plasma on trough field lines is directly related to the polar wind, as implied by the studies referred to in the introduction, a fast-moving upward flow of H^+ ions might be expected in the trough.

For simplicity, the He^+ and N^+ ions are ignored in our dynamic state model, and the plasma is assumed to consist of H^+ moving with a net upward velocity through a stationary O^+ distribution. The steady state continuity and momentum equations for O^+ and H^+ are integrated along the field lines allowing for the existence of transport fluxes of H^+ perpendicular to the field direction in order that nonvanishing fluxes of H^+ along the field lines can exist. At altitudes below 1000 km, where chemical reactions are important, the neutral atmosphere must be taken into account; the model atmosphere adopted is that of Jacchia (1964). The mathematical flux model and the mechanics of the ionospheric processes included in our dynamic state computations are discussed in detail by Mayr et al. (1970).

The initial model computations were performed for winter conditions, the objective being to find a flow profile for the H^+ ions which would account for the observed H^+ and O^+ concentration distributions (Figure 4). (Similar calculations were also made for the equinox trough data of Figure 3, but due to the restricted altitude range of these measurements and the similarity between the winter and equinox data, only the winter study will be presented in detail.) The following boundary conditions, characteristic of the winter 1966 period, were applied to the model computation: $[O]_{500km} = 6.4 \times 10^4/cm^3$, $[H]_{500km} = 1.0 \times 10^5/cm^3$, and $T_{neutral} = 830°K$. Since, as noted previously, the major ion (O^+) distribution could be accounted for by an isothermal plasma state (see Figure 4), the ion-electron temperature above 1000 km was assumed constant at 2200°K, corresponding to a thermal speed of 7.4 km/sec for the H^+ ions.

A velocity profile (Figure 7) was determined for the H^+ ions which produces model concentrations in agreement with the winter trough observations. As shown in Figure 8, the H^+ concentration computed with this upward flow decreases with increasing altitude even though O^+ is the major ion. Because of their low mass it is probable that He^+ ions also flow upward in the trough region, which would account for the observed decrease in He^+ concentration with altitude.

Based on these model studies, then, it appears that a dynamic state of upward moving light ions characterizes the trough field lines at midday.

It should be noted that, in accord with polar wind theories which predict a high speed upward H^+ flow, the present flux calculations imply that the H^+ flow velocity (Figure 7) on midday trough field lines approaches the H^+ thermal velocity ($\sim$7 km/sec) at the high altitude limit of the Explorer 32 measurements—at 2500 km the mach number is approximately 0.85. Hence the trough ion composition measurements are consistent with the concept of the polar wind convecting onto closed magnetic field lines resulting in a 'trough wind'.

CONCLUSIONS

Analysis of the variation with altitude of the concentrations of the primary atmospheric ions in the midlatitude trough and within the plasmasphere has revealed that quite different mechanisms govern the ion distributions in these regions. While the plasmasphere profiles can be reproduced by a model based on a stationary state in diffusive equilibrium, it has only been possible to duplicate the trough distributions by invoking the existence of upward directed light ion fluxes with velocities at 2500 km altitude approaching the ion thermal speed. This result is interpreted as evidence for a 'trough wind', an upward flow of H^+ and He^+ along closed trough field lines outside the plasmasphere (Figure 1). Unfortunately, the limited altitude extent of the data presented here precludes the determination of whether or not the H^+ flow on the trough field lines attains supersonic velocity, as does the polar wind. A definitive study of the trough wind, including its composition, magnitude, variation, and its relationship to the polar wind, will require comprehensive measurements of thermal ion composition and flux over an altitude range extending to several thousand kilometers in the trough and polar regions.

REFERENCES

Angerami, J. J. and J. O. Thomas, Studies of planetary atmospheres, 1, The distribution of electrons and ions in the earth's exosphere, J. Geophys. Res., 69, 4537, 1964.

Axford, W. I., The polar wind and the terrestrial helium budget, J. Geophys. Res., 73, 6855, 1968.

Axford, W. I., The plasma-pause and the polar wind, Appleton Memorial Lecture, URSI General Assembly, Ottawa, Canada, August 1969.

Banks, P. M. and T. E. Holzer, The polar wind, J. Geophys. Res., 73, 6846, 1968.

Banks, P. M. and T. E. Holzer, J. Geophys. Res., 74, 3734, 1969a.

Banks, P. M. and T. E. Holzer, Features of plasma transport in the upper atmosphere, J. Geophys. Res., 74, 6304, 1969b.

Banks, P. M. and T. E. Holzer, High-latitude plasma transport: the polar wind, J. Geophys. Res., 74, 6317, 1969c.

Bauer, S. J. and B. V. Krishnamurthy, Behavior of the topside ionosphere during a great magnetic storm, Planet. Space Sci., 16, 653, 1968.

Brinton, H. C., H. G. Mayr, R. A. Pickett, and H. A. Taylor, Jr., The effect of atmospheric winds on the O^+-H^+ transition level, NASA/GSFC Document X-621-69-186, May 1969, to be published in Space Research X, 1970.

Brinton, H. C., R. A. Pickett, and H. A. Taylor, Jr., Diurnal and seasonal variation of atmospheric ion composition; correlation with solar zenith angle, J. Geophys. Res., 74, 4064, 1969.

Chandra, S., B. E. Troy, Jr., J. L. Donley, and R. E. Bourdeau, OGO 4 observations of ion composition and temperatures in the topside ionosphere, J. Geophys. Res., 75, 3867, 1970.

Hoffman, J. H., Ion mass spectrometer on Explorer XXXI satellite, Proc. IEEE, 57, 1063, 1969.

Jacchia, L. G., Static diffusion models of the upper atmosphere with empirical temperature profiles, Special Report 170, Smithsonian Institution Astrophysical Observatory, Cambridge, Mass., December, 1964.

Mahajan, K. K. and L. H. Brace, Latitudinal observations of the thermal balance in the nighttime protonosphere, J. Geophys. Res., 74, 5099, 1969.

Mayr, H. G., J. M. Grebowsky, and H. A. Taylor, Jr., Study of the thermal plasma on closed field lines outside the plasmasphere, NASA/GSFC Document X-621-69-299, July 1969, accepted for publication in Planet. Space Sci., 1970.

Miller, N. J., The midlatitude ionization trough during the rising solar cycle, NASA/GSFC Document X-621-69-330, August 1969, submitted to J. Geophys. Res., 1970.

Nishida, A., Formation of plasmapause, or magnetospheric plasma knee, by the combined action of magnetospheric convection and plasma escape from the tail, J. Geophys. Res., 71, 5669, 1966.

Sanatani, S. and W. B. Hanson, Plasma temperatures in the magnetosphere, J. Geophys. Res., 75, 769, 1970.

Schunk, R. and J. C. G. Walker, Thermal diffusion in the topside ionosphere for mixtures which include multiply-charged ions, Planet. Space Sci., 17, 853, 1969.

Taylor, H. A., Jr., The longitudinal variation in the O^+ - H^+ transition level, Trans. A.G.U., 51, 587, 1970a.

Taylor, H. A., Jr., Evidence of solar geomagnetic seasonal control of the topside ionosphere, NASA/GSFC Document X-621-70-258, June 1970, submitted to Planet. Space Sci., 1970b.

Taylor, H. A., Jr., H. C. Brinton, M. W. Pharo, III, and N. K. Rahman, Thermal ions in the exosphere; evidence of solar and geomagnetic control, J. Geophys. Res., 73, 5521, 1968.

Taylor, H. A., Jr., H. G. Mayr, and H. C. Brinton, Observations of hydrogen and helium ions during a period of rising solar activity, NASA/GSFC Document X-621-69-187, May 1969, to be published in Space Research X, 1970.

Walker, J. C. G., Thermal diffusion in the topside ionosphere, Planet. Space Sci., 15, 1151, 1967.

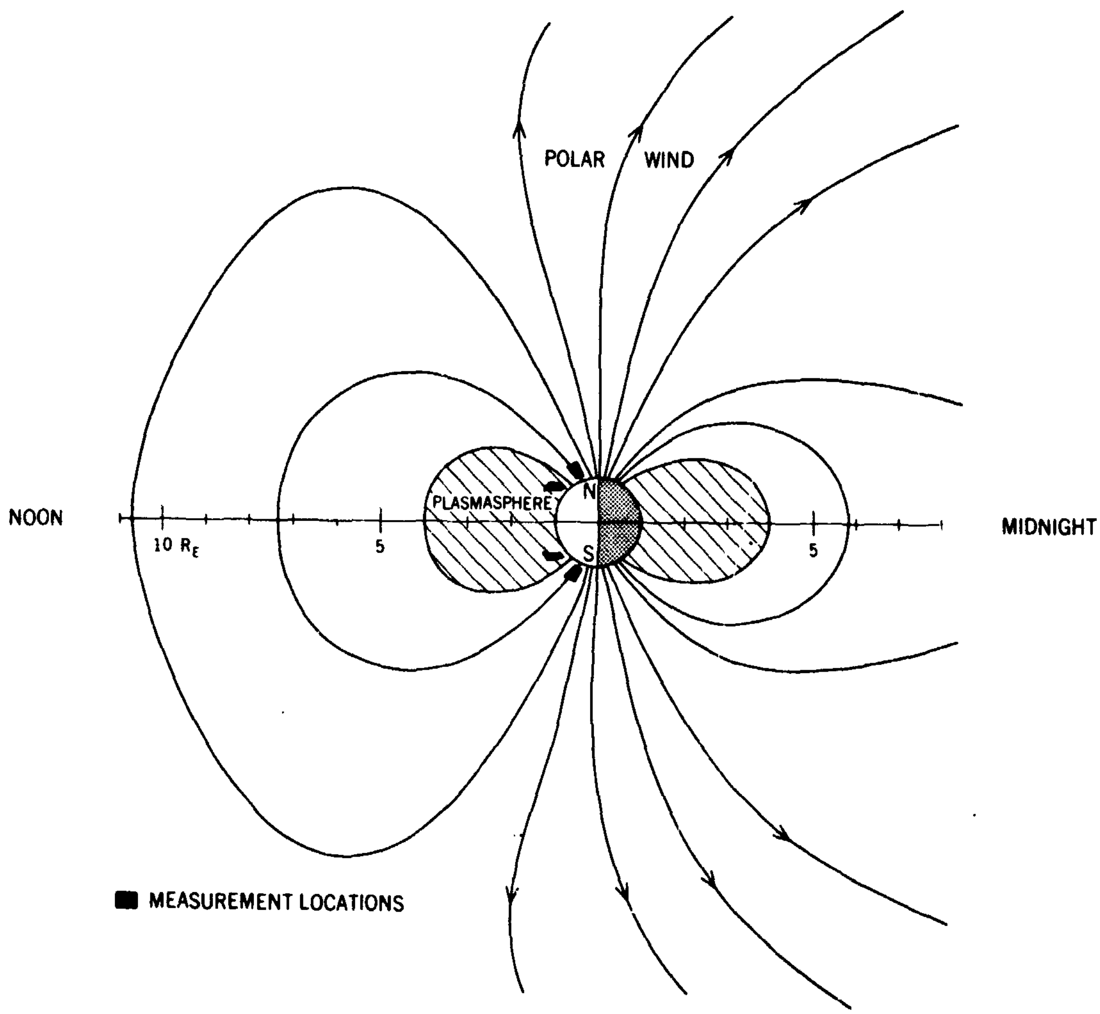

Figure 1. Simplified diagram of magnetosphere, showing locations of ion composition measurements.

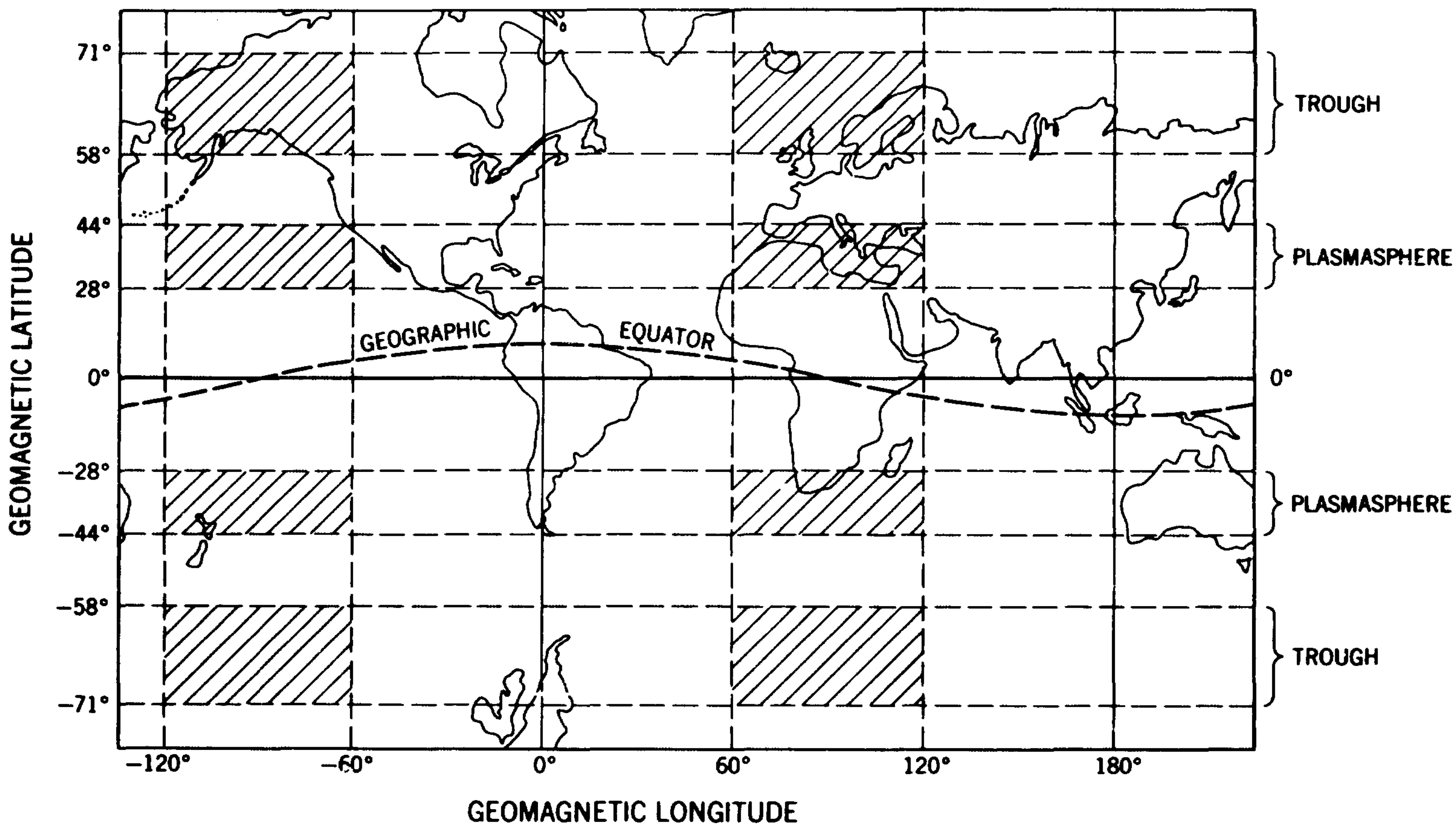

Figure 2. Shaded areas indicate ranges of geomagnetic latitude and longitude in which trough and plasmasphere data were obtained.

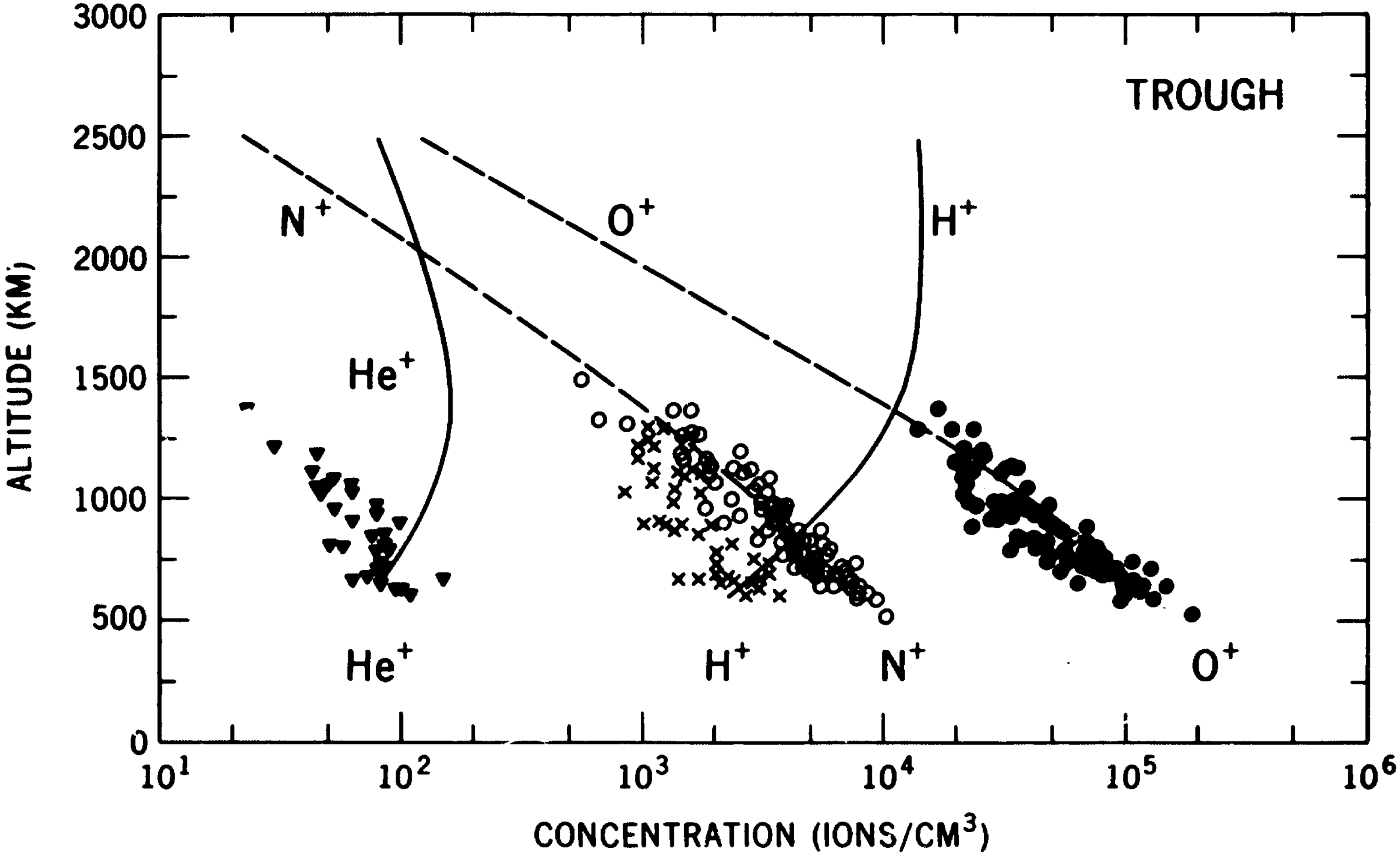

Figure 3. Altitude variation of ion concentrations in midlatitude trough region under daytime equinox conditions. Local time: 0900-1500; L: 5.0-10.5. Model profiles, calculated assuming isothermal diffusive equilibrium, are shown for comparison.

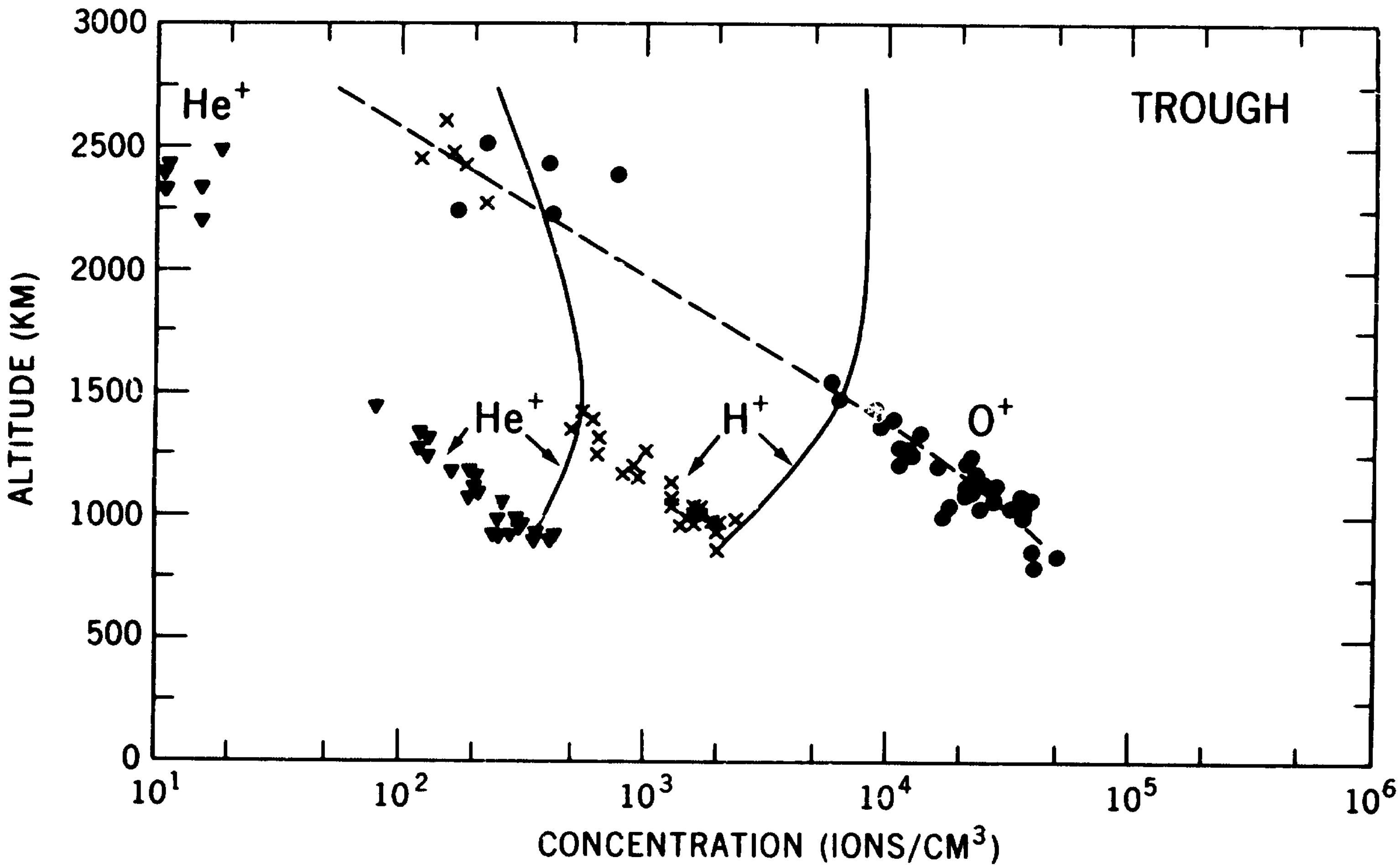

Figure 4. Altitude variation of ion concentrations in midlatitude trough region under daytime winter conditions. Local time: 0900–1500; L: 5.0–10.5. Model profiles, calculated assuming isothermal diffusive equilibrium, are shown for comparison.

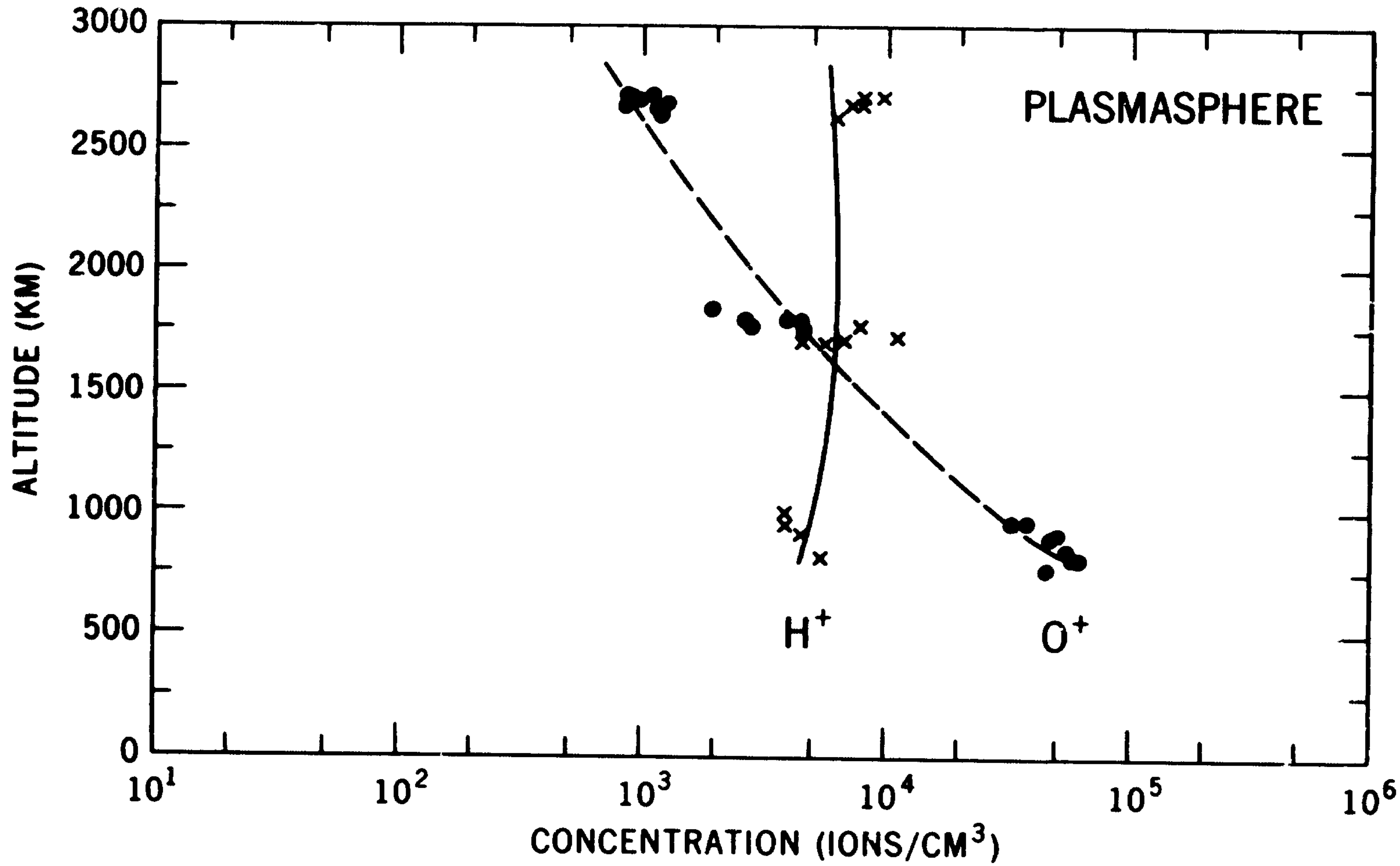

Figure 5. Altitude variation of O^+ and H^+ concentrations inside the plasmasphere under daytime equinox conditions. Local time: 0900–1500; L: 1.8–2.2. Diffusive equilibrium model profiles, calculated assuming temperature variations along field lines (Figure 6) and resultant thermal diffusion, are shown for comparison.

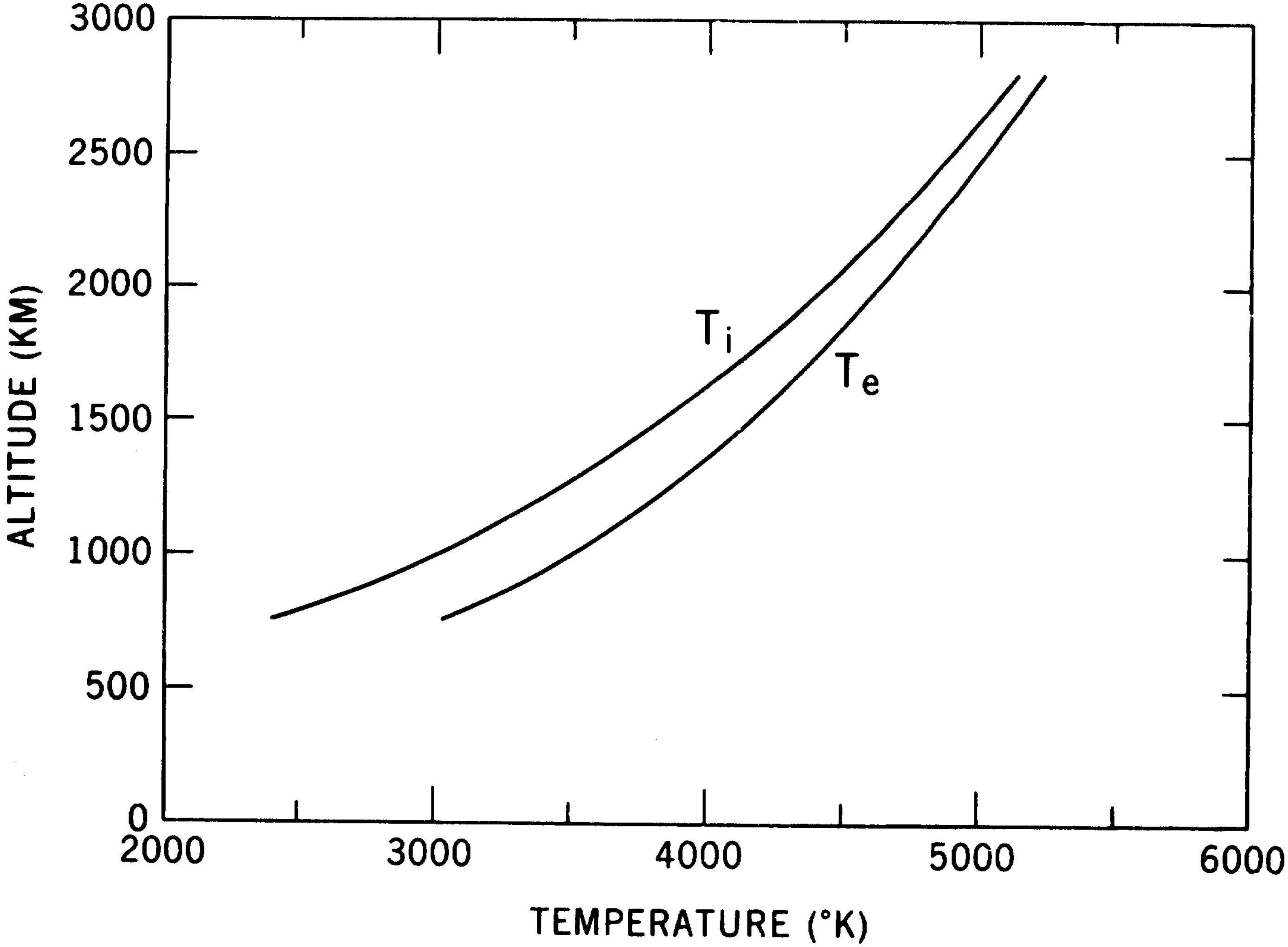

Figure 6. Temperature profiles along field lines used in the derivation of model plasmasphere ion distributions shown in Figure 5.

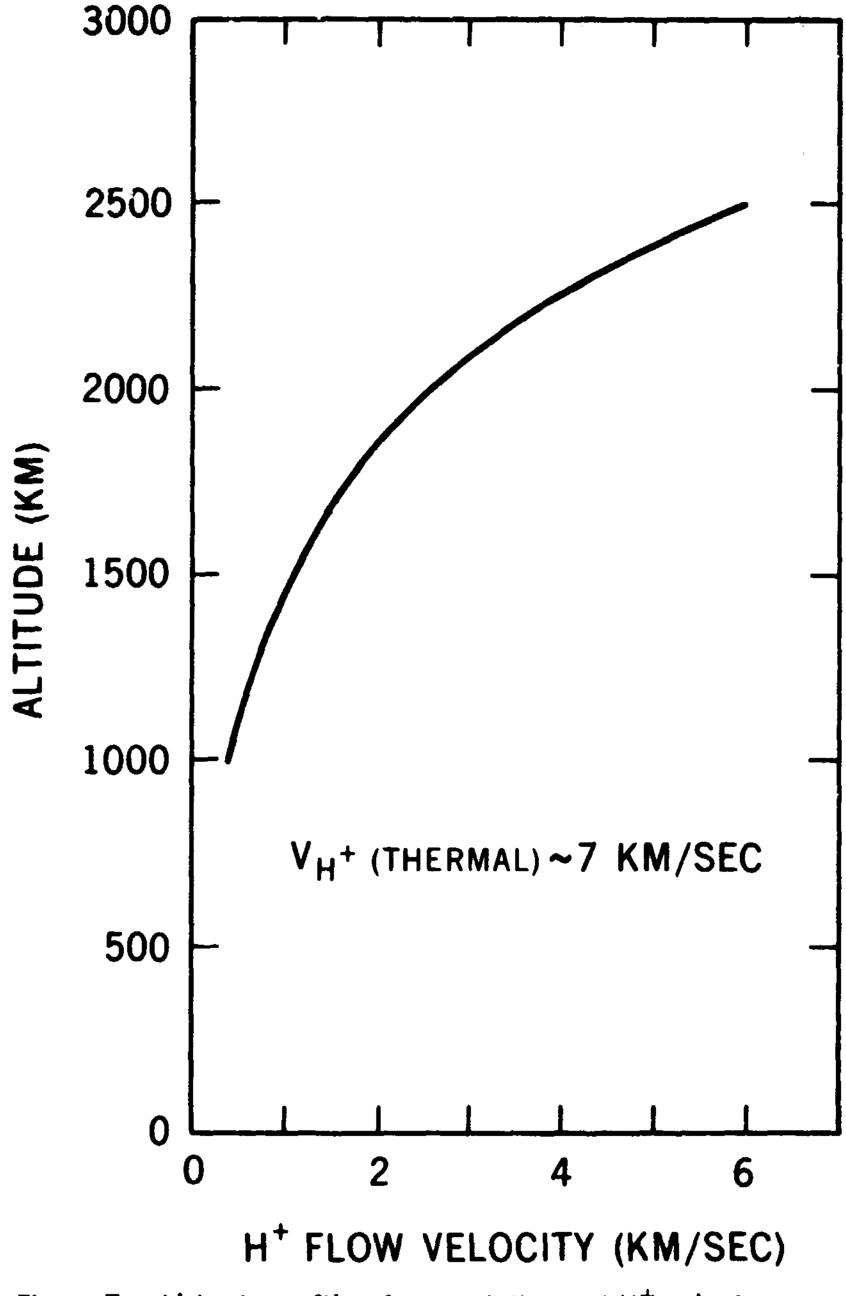

Figure 7. Altitude profile of upward directed H^+ velocity computed using the flux model of Mayr et al. (1970). Invoking the existence of such a flow in the trough region leads to the derivation of model ion profiles which fit the observed distributions (Figure 8).

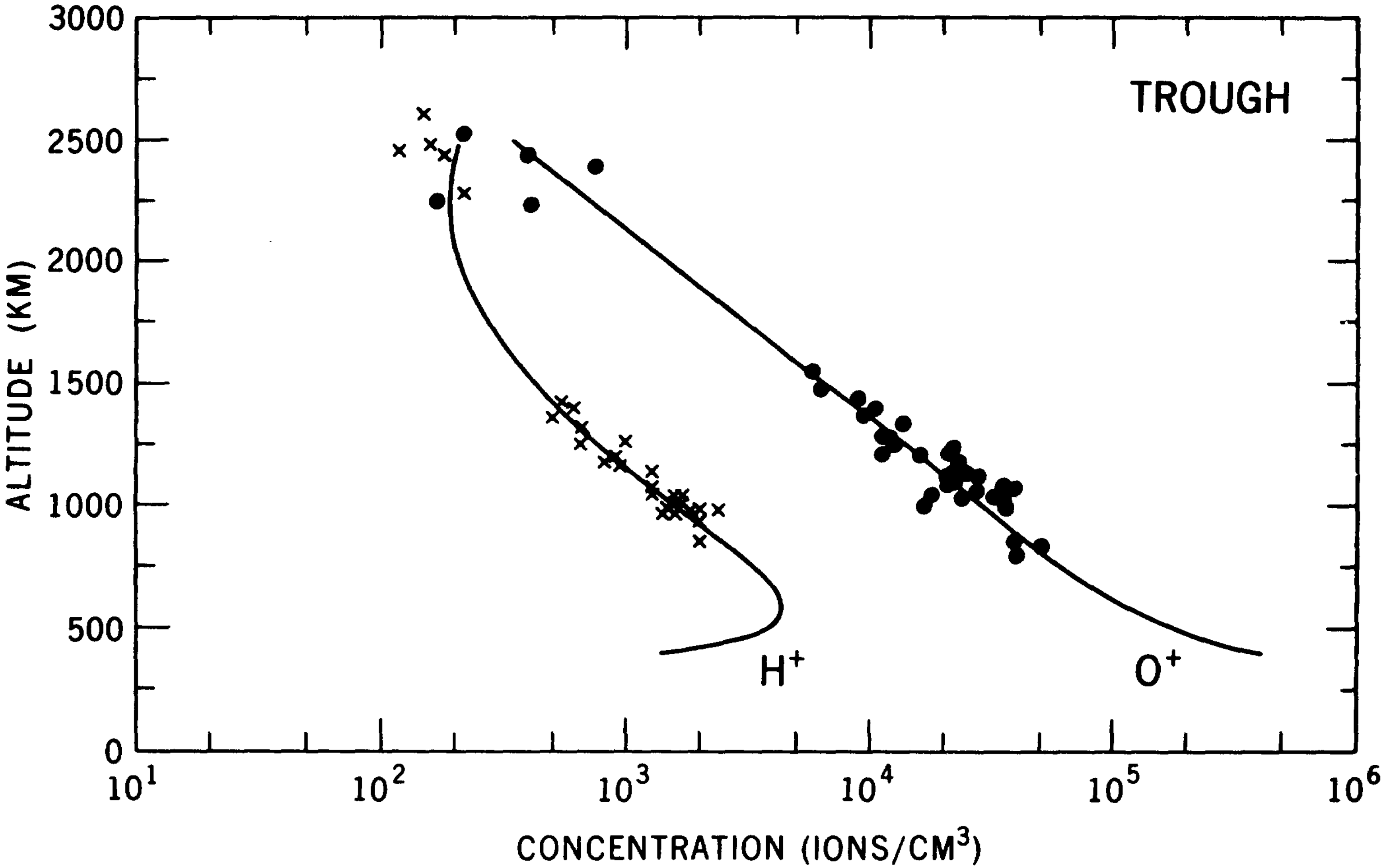

Figure 8. Comparison of observed altitude profiles of O^+ and H^+ in the trough region (from Figure 4) with model distributions invoking an upward H^+ flux with velocity profile depicted in Figure 7.