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A MASS SPECTROMETRIC DETERMINATION OF THE COMPOSITION OF THE NIGHTTIME TOPSIDE IONOSPHERE

John H. Hoffman[1]

E. O. Hulburt Center for Space Research
Naval Research Laboratory
Washington, D. C. 20390

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[1] Now at Southwest Center for Advanced Studies, Dallas, Texas.

Abstract

The concentrations of H^+, He^+ and O^+ were determined as a function of altitude by means of a magnetic mass spectrometer flown on an Argo D-4 rocket at local midnight on January 17, 1964, from Wallops Island, Virginia. The lower ionosphere consists primarily of O^+ with a transition to H^+ as the predominant ion at 430 km. He^+ never becomes the predominant species, its maximum density being $5 \times 10^3/cm^3$. The temperature calculated from scale heights of the various constituents is 700° ± 100°K. The neutral hydrogen density at 350 km is calculated, assuming chemical equilibrium between H^+ and O^+, to be $5 \times 10^6/cm^3$.

INTRODUCTION

A measurement of the composition of the topside ionosphere in the mass range 1 to 32 AMU was obtained by the use of a magnetic mass spectrometer flown on an Argo D-4 rocket (NASA 8.32 DA), launched from Wallops Island, Virginia, at 0001 EST (0501 GMT) on 17 January 1964. The rocket, carrying a 125 lb. payload reached an altitude of 926 km. Results showing the positive ion distributions in the nighttime ionosphere are reported here.

APPARATUS

The mass spectrometer was a 1-1/2" radius sector-field single focusing magnetic instrument operated with a permanent magnet of 2200 gauss and a swept ion accelerating voltage. The entrance aperture, which was mounted so its normal was transverse to the rocket spin axis, was at -8 volts. No ion source was employed in the instrument since it was designed to measure the relative abundances of the positive ions formed in the upper atmosphere by natural processes. Ambient ions from the ionosphere entered the mass spectrometer entrance aperture, then were accelerated to the magnetic analyzer and passed into a magnetic strip-type electron multiplier which had a current gain of the order of 2×10^4. A multi-range electrometer amplifier measured the output current from the multiplier. Surrounding the entrance aperture of the spectrometer was an annular plate which served as an ion trap to measure the total positive ion density profile.

RESULTS

Data from the ion trap were obtained from nose cone ejection, approximately 200 km, to peak of flight, 926 km, and down to 150 km on the descent. When plotted as a function of altitude, the ion current collected by the trap exhibits a maximum at the same altitude as the F_2 maximum, which was determined by the Wallops Island ionosonde (Lohr 1964). This maximum of the ion current profile was equated to the F_2 maximum ion density. Assuming that the ion current and ion density are linearly related and independent of rocket velocity and ion species (there was a -8 volt draw-in potential), then, the ion current profile is an ion density profile normalized at the F_2 maximum. The ion density profiles so obtained are shown as curves n_i in Figure 1. Direction of the arrows indicates ascent or descent of the rocket. The steep decrease above the F_2 maximum and the sharp break in the curve at approximately 500 km should be noted. The descent curve has roughly the same shape as the ascent, but the density does not increase as rapidly with decreasing altitude from the peak of flight. Also, the maximum is more than a factor of two below the ascent density maximum although it occurs at the same altitude.

Mass spectra were obtained from the time of high voltage turn on (10 sec. after nose cone ejection) or 240 km, to approximately 200 km on the descent. Peaks appeared in the spectra at mass numbers 1(H^+), 4(He^+), 14(N^+) and 16(O^+).

The raw data exhibit a modulation of the ion peak amplitude as a function of roll position of the rocket. The rocket is moving with a velocity almost equal to the thermal velocity of the light mass ions and greater than the velocity of the heavy mass ions. Therefore, the modulation observed results from an enhancement of ion current collected by the mass spectrometer in the ram position (when the entrance aperture normal is aligned with the rocket velocity vector) and a depletion of ions collected in the wake position. The amplitude of the roll modulation is strongly mass dependent (ion velocity dependent), it being about 1.5 for hydrogen, 3.5 for helium and greater than 100 for oxygen. As a result, oxygen and nitrogen peaks appeared in only a few spectra taken during the lower portion of flight (when the mass spectrometer was nearly in the ram position). Nitrogen was present to only about 10% of the oxygen. The oxygen ions have an energy of the order of a volt with respect to the rocket due to the rocket velocity. The acceptance angle of the mass spectrometer for ions of this energy is quite narrow. The result is that oxygen ions (and nitrogen) are highly discriminated against at all angles of attack except near the ram condition, i.e., when the entrance aperture normal and velocity vector are parallel. This condition is greatly reduced for H^+ and He^+ and corrections for roll modulation were made for these ions.

The H^+ and He^+ ion data, after being corrected for roll modulation and mass discrimination of the mass spectrometer, are shown plotted against altitude in Figure 1. Again, the arrows indicate ascent or descent portions of the flight. Since H^+ and He^+ peaks are the only ones present in the spectra at the peak of flight, the sum of these two ion currents was equated to the total ion density at the peak of flight, thus giving an absolute calibration to the ion density profiles of H^+ and He^+. It was found that the sum of these ion current profiles agreed very closely with that of the total ion density from the peak of flight to nearly 500 km on both the ascent and descent.

Because of the roll modulation phenomenon, there were too few peaks of O^+ to plot a good profile for oxygen. Therefore, since the H^+, He^+ and O^+ (with 10% N^+) were the only peaks observed in the spectra, and since above 550 km the sum of the H^+ and He^+ density profiles agrees with the total density profile, subtraction of the H^+ and He^+densities from the total yields a curve of the O^+ (plus N^+) density. This derived O^+ profile is shown as the O^+ curve in Figure 1. The few observed O^+ peaks confirm that O^+ is the predominant ion in the region of the F_2 maximum and also confirm the general shape of the derived O^+ curve.

The H^+ ion density increases rapidly from 250 km and reaches a maximum at 450 km, about the altitude of the cross-over with O^+, then falls slowly to the peak of flight. He^+ rises rapidly from 300 km to a peak at 450 km, then decreases to apogee but never becomes the predominant ion in the ionosphere. The descent curve for helium does not exhibit a maximum, but is rather flat down to 400 km; it then drops off rapidly. This flatness contributes to the flatness of the descending total ion density curve down to the altitude where

O^+ ions become predominant. The O^+ curves follow the total density curves up to an altitude of 430 km where H^+ becomes the dominant ion. Above this altitude the O^+ density decreases at a greater rate because the O^+ is now a minor ion. (Mange, 1960). The differences between the up and downleg distributions may be due to the fact that the up and downleg trajectories are separated by several hundred km and perhaps a different ionosphere is being sampled. Wallops Island is approximately at 38° N and 75° W, and the launch azimuth was 93°. The horizontal range of the flight was nearly 800 km.

Figure 2 shows a mean ion mass curve plotted from the data of Figure 1 and assuming only H^+, He^+ and O^+ ions to be present. Since it is assumed that only O^+ exists at the F_2 maximum, 280 km, (the molecular ions, NO^+ and O_2^+ being of negligible concentration at this altitude) the curves start at mass 16. At the peak altitude the mean ion mass has fallen to 1.3. The rapid decrease in mean ion mass is due to the direct crossover of O^+ to H^+, at 430 km rather than to a He^+ band first and then to H^+.

DISCUSSION

Ions of both hydrogen and helium, as well as oxygen and nitrogen were observed in the mass spectra. Nicolet (1961) first postulated the existence of helium as an important constituent of the earth's upper atmosphere. Hanson (1962) and Bourdeau et al. (1962) inferred the existence of helium ions from data obtained by means of ion trap experiments. Taylor (1963) made a direct measurement of helium ions using a Bennett radio-frequency mass spectrometer on an Argo D-4 rocket.

While helium ions were observed in the experiment being reported in the present paper, they are never the predominant ion. The transition from heavy to light ions goes directly from O^+ to H^+. The maximum density of He^+ is $5 \times 10^3/cm^3$. 15% of the total density.

A few mass spectra exhibited N^+ peaks which have an abundance of approximately 10% of the O^+ near the F_2 maximum. There are not enough data to treat N^+ separately. Therefore, the N^+ data are combined with the O^+ data in the derived O^+ curve as described above.

If chemical equilibrium is assumed to exist below the crossover altitude between H^+ and O^+, then H^+ is both formed and lost from the ionosphere by the reaction (Hanson and Ortenburger, 1961).

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

The chemical equilibrium distribution for H^+ is given by

$$n(H^+) = 9/8 \; \frac{n(H)\, n(O^+)}{n(O)} \qquad (2)$$

where 9/8 represents the ratio of the product of statistical weights for the two processes of reaction (1). Assuming the atmospheric constituents H and O to be distributed exponentially in the region where O^+ is the predominant ion (below 430 km), equation (2) leads to

$$n(H^+) = A \exp (Z/\underline{H}(7)) \tag{3}$$

where A is a constant, $\underline{H}(7)$ is the scale height with an effective mass of 7 AMU and Z is the reduced altitude (Hanson, 1962). This means that H^+ in chemical equilibrium is increasing with altitude in agreement with the data of Figure 1. The temperature obtained from the scale height of the lower portion of the H^+ ascent curve, between 300 and 350 km, assuming an isothermal atmosphere and using an effective mass of 7 AMU, is 400 ± 200° K.

Helium ions are produced by photoionization of neutral helium and lost by charge transfer reactions with molecular atmospheric constituents. The most important loss process is (Bauer 1965).

$$He^+ + N_2 \rightarrow He + N^+ + N \tag{4}$$

A similar reaction involving O_2 is probably of lesser importance since $n(N_2) >> n(O_2)$ and the rate coefficients, k_4, for both the N_2 and O_2 reactions are equal and have a value of 10^{-9} cm^3 sec^{-1} (Ferguson et. al., 1964) as measured in the laboratory.

The chemical equilibrium distribution for He^+ is therefore given by

$$n(He^+) = \frac{I_{He} n(He)}{k_4 \; n(N_2)} \tag{5}$$

where $I_{He} = 3 \times 10^{-8}$ sec^{-1} is the ionization rate coefficient for He. It follows that

$$n(He^{+}) = B \exp (Z/\underline{H} (24)) \qquad (6)$$

The data from this experiment were obtained at night where no photoionization takes place. Only the loss mechanism is operative. Thus, it is not meaningful to calculate a value of k or a scale height temperature based on Equation 5.

In the case of diffusive equilibrium, above the transition to the predominantly H^{+} ionosphere, the equilibrium distributions are given by (Mange, 1960)

$$\frac{d (\ln n_i)}{dz} = \left[\frac{1}{1 - \frac{m_+}{2 m_i}} H_i \right]^{-1} \qquad (7)$$

where m_+ is the mean ionic mass and $H_i = \frac{kT}{m_i g}$ is the scale height of the corresponding neutral species. It is assumed that $T_i = T_e$. At 900 km, $m_+ = 1.3$ (Figure 2). The scale height for H^{+} (ascending curve) is 1600 ±400 km (reduced altitude.) The corresponding temperature is 670° ±400°K. For helium at 900 km, the scale height is 182 ±10 km and the temperature is 700° ±50°K. For oxygen, the scale height is 35 ±5 km giving a temperature of 670° ±100°K. The agreement between these scale height temperatures is fortuitous. The assumption has been made here that we are dealing with an isothermal ionosphere, and that $T_i = T_e$. Brace et. al. (1966) have shown that at local midnight from 40°N southward, a wide low trough exists in T_e. A 700°

value for T_i is consistent with his findings. The large uncertainty in the hydrogen temperature arises from two sources: (a) the slope of the H^+ distribution is very steep thus introducing a large uncertainty in the scale height; (b) the mean ion mass is 1.3 ± 0.3 giving rise to a large uncertainty in the value of $1 - m_+/2m_i$ for $m_i = 1$ due to the uncertainty in m^+. The latter error is greatly reduced for $m_i = 4$ or 16.

Figure 3 shows a plot of the altitude distributions of H^+/He^+ and H^+/O^+. It can be shown that for the case of diffusive equilibrium (Bauer, 1964) that

$$\frac{n(H^+)}{n(He^+)} = C \exp\left[\frac{Z}{\underline{H}\ (3)}\right] \qquad (8)$$

C is a constant and $\underline{H}$ (3) corresponds to a scale height for an effective mass of 3 AMU. The dashed line $\underline{H}$ (3) is a plot of equation 8 for T = 700°. The slope of this curve is a function only of temperature and not mean ion mass. Likewise, the slope of the ratio of the measured H^+/He^+ densities is independent of the mean ion mass. All of these data, therefore, indicate that a temperature of 700° ±100° was characteristic of the upper ionosphere at the time of this flight.

Equation (2) may be used to obtain the concentration of neutral hydrogen in the region of chemical equilibrium. Using the model of Jacchia (1965) at 700° for the oxygen concentrations and the $n(H^+)/n(O^+)$ values from Figure 3, the neutral hydrogen density at 350 km is

$5 \pm 2 \times 10^6/cm^3$. Donahue (1965) gives a value, derived from photometric observations, of 2×10^5 at 350 km for 700°. There is an obvious inconsistency between these data. Joseph (1966) has calculated the $n(H^+)/n(O^+)$ as a function of temperature, assuming this ratio is only a function of temperature. The measured transition altitude of 430 km agrees closely with his calculated value for 700°.

CONCLUSION

The concentrations of H^+, He^+ and O^+ were determined as a function of altitude by a magnetic mass spectrometer flown at local midnight on an Argo D-4 rocket. The transition between a predominantly O^+ ionosphere to one predominantly of H^+ occurs at 430 km. Helium is never the predominant ion species, its maximum density being 15% of the total at 450 km. The temperature calculated from the scale heights of the various ion constituents is 700°. The neutral hydrogen concentration at 350 km is calculated, assuming chemical equilibrium between H^+ and O^+, to be $5 \times 10^6/cm^3$.

Data from the Arecibo Radar Backscatter Station are in agreement with those reported here. Carlson and Gordon (1966) have observed He^+ to be a minor constituent at all times (about 20% or less) and to have a density maximum at about 450 to 500 km in the winter night (December, 1964). At local winter midnight their O^+ to H^+ transition occurs at about 500 km, the ionosphere being 95% O^+ at 375 km and 80% H^+ at 600 km.

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CAPTIONS FOR FIGURES

Figure 1. Concentrations of H^+, He^+ and O^+ and total ion density as a function of altitude. Direction of arrows indicates up or downleg of flight. F_2 maximum on upleg was normalized to density at that point obtained by Wallops Island ionosonde at time of flight.

Figure 2. Mean ion mass as a function of altitude from data plotted in Figure 1.

Figure 3. Ratios of ion constituents as a function of altitude. $\underline{H}(3)$ is a theoretical distribution of H^+/He^+ at 700°. See text.

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INDEX WORDS

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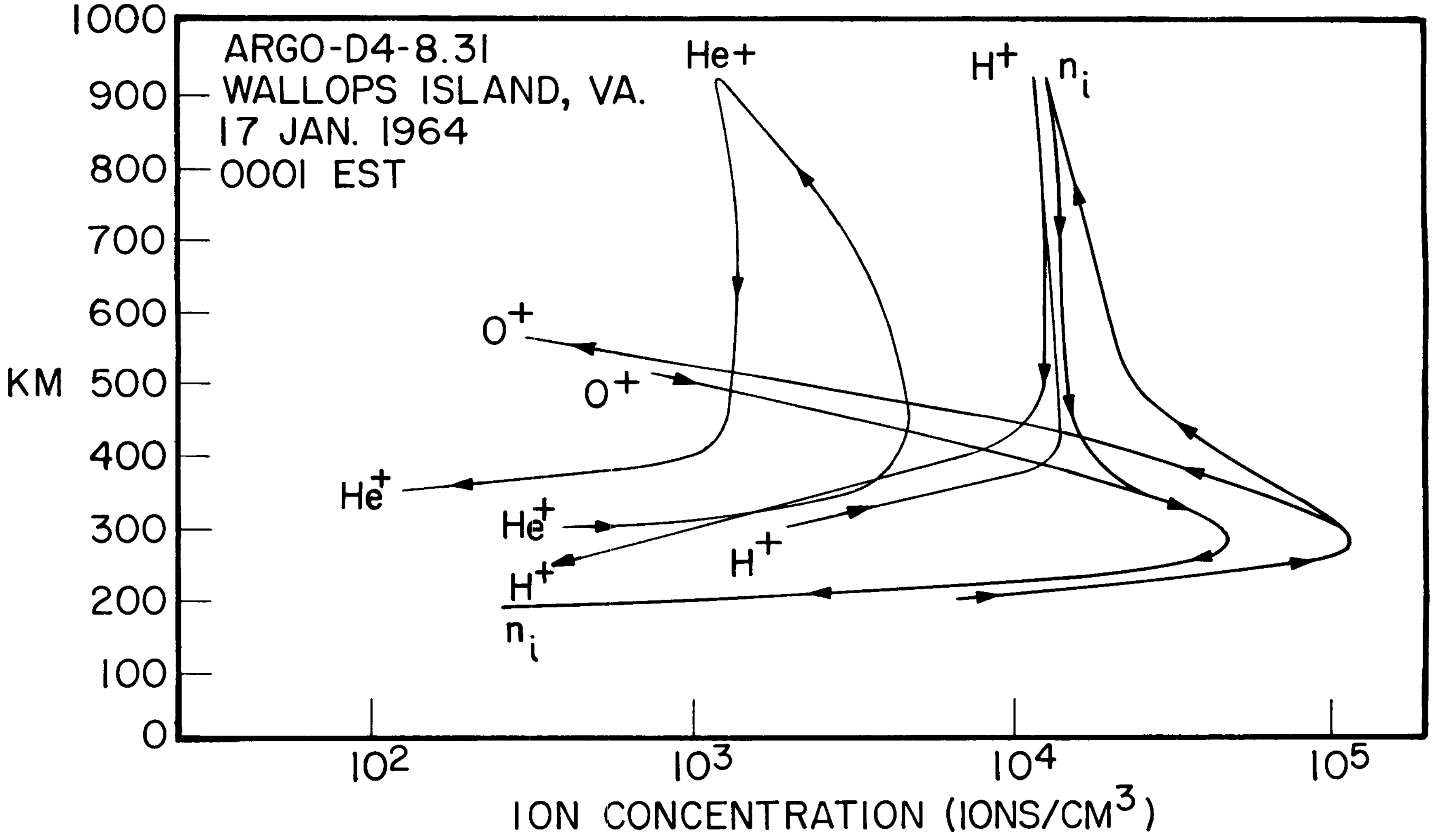

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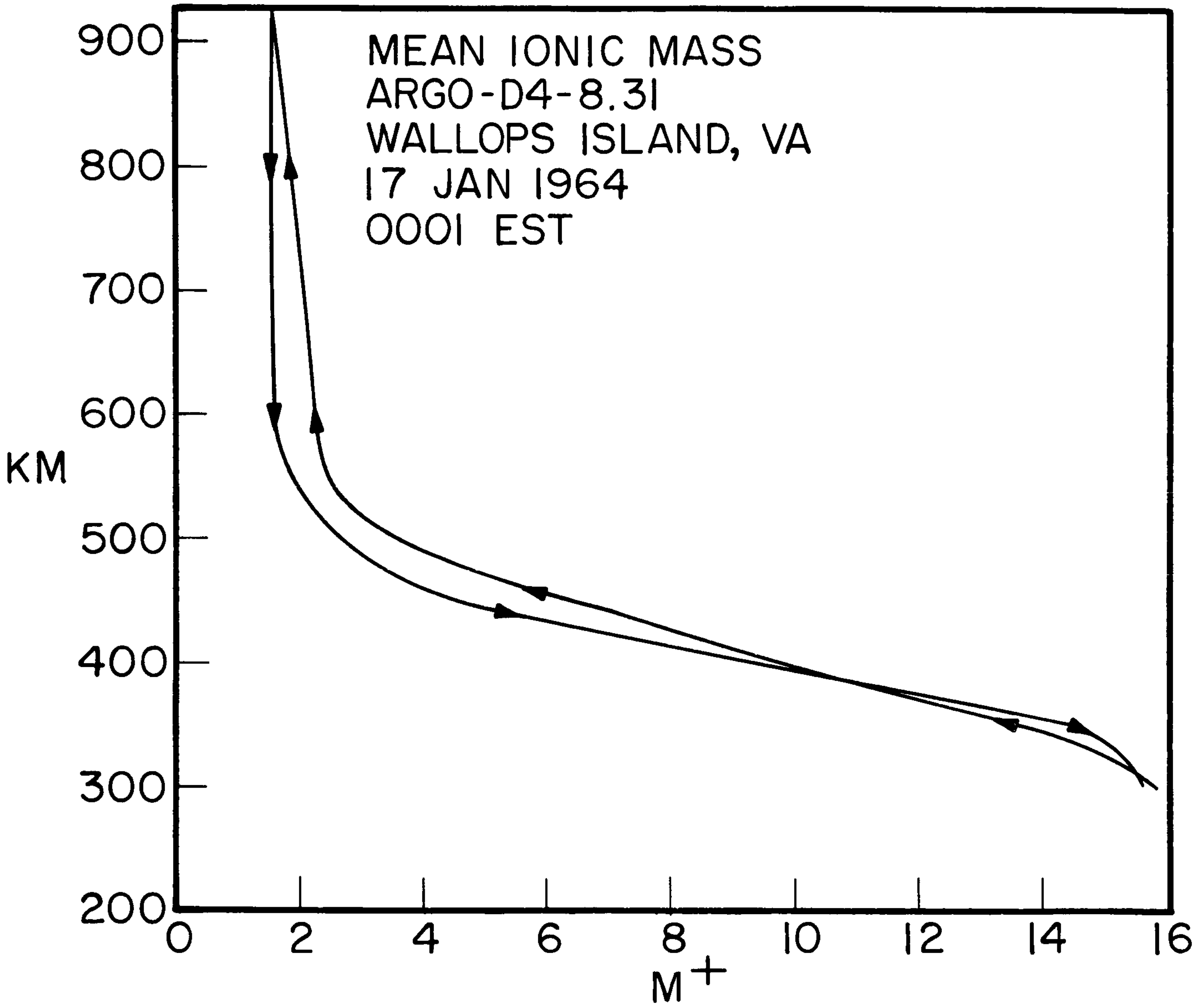
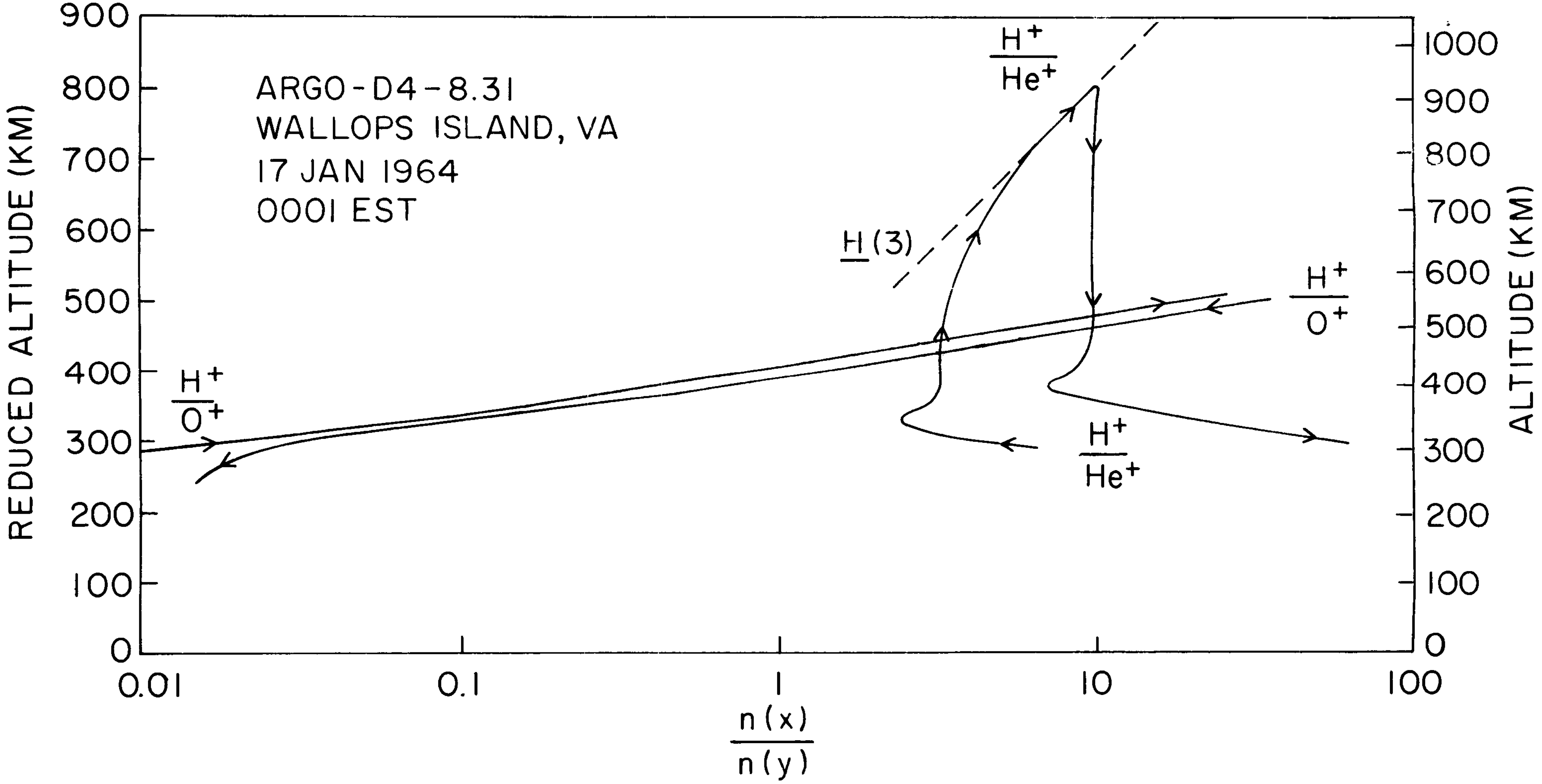


Figure 2. Mean ion mass as a function of altitude from data plotted in Figure 1.



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