EXPLORER XXXI
ION MASS SPECTROMETER EXPERIMENT

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Composition Measurements of the Topside Ionosphere

Abstract. *Data from a magnetic mass spectrometer flown on the Explorer 31 satellite show that the ionosphere above 1000 kilometers usually consists of hydrogen ions as the predominant species. Between this altitude and perigee (500 kilometers) the dominant ion species shifts to atomic oxygen, with a significant amount of atomic nitrogen ions also present. Helium ions are present in small quantities at all altitudes. Other minor ions observed are those of 2, 7, 8, 15, 18, and 20 atomic mass units.*

On 29 November 1965 the Explorer 31 satellite (Direct Measurements Explorer) was launched piggyback with the Canadian Alouette II Topside Sounder from the Western Test Range. The satellites were placed in an 80° prograde, 3000-km-apogee, 500-km-perigee orbit. The Explorer 31 satellite contains experiments designed to measure directly various properties of the earth's ionosphere. This report gives some preliminary data from the magnetic mass spectrometer experiment which identifies the various positive ion species in the ionosphere and gives their relative abundances.

The instrumentation flown in this experiment consists of a small magnetic sector-field mass spectrometer. There is no ion source employed in the instrument, since it is designed to measure the relative abundances of the positive ions formed in the upper atmosphere by natural processes. The operating potentials are adjusted to permit thermal energy ambient ions to enter the mass spectrometer through an aperture in the side of the satellite. These ions then pass through the magnetic analyzer having a 1½-inch (3.8-cm) radius (the permanent magnet has a field strength of 2200 gauss) and into an electron multiplier. A 5-decade logarithmic solid-state electrometer amplifier measures the output current from the electron multiplier. The mass spectrum from 1 to 22 amu (atomic mass units) is continually swept by an exponentially decreasing voltage having a 3-second period.

Figure 1 shows a portion of an analog telemetry record taken from the satellite. A monitor of the sweep voltage is shown in the top channel and the mass spectrum appears below. The mass peaks are identified by mass number (amu). The amplitude of the peaks is given in volts, this voltage being proportional to the logarithm of the ion current detected by the electron multiplier for each ion species. This ion current is a function of the number density of that species in the vicinity of the satellite.

The satellite is oriented so that its spin axis is normal to the orbital plane. Thus, the mass spectrometer entrance aperture on the side of the satellite alternately points along the satellite velocity vector and opposite to it. Since the satellite is traveling at a speed equal to or greater than the mean velocity of the ambient ions, there is a ram and wake effect exhibited in the data as a modulation of the ion peak amplitudes. The satellite spin period is approximately 7 sweep periods. Figure 1 shows one roll-modulation cycle of data. The mass 1 peak amplitude is relatively constant while the heavy ion (mass 14, 16, 18) peaks are absent in nearly half of the spectra.

Figure 2 is a plot of the peak amplitudes of successive mass spectra as a function of time. These data were obtained from the Fort Myers, Fla., tracking station on 14 March 1966 between 1331 and 1334 GMT. The satellite altitude was 600 km at the left side and 700 km at the right side of the figure. It should be noted here that the amplitude of the roll modulation is a strong function of ion mass. For hydrogen (H^+), it is about 1 order of magnitude; for helium (He^+), 2½ orders of magnitude; and for oxygen (O^+), more than the 5 orders of magnitude shown in the figure. This results from the satellite velocity being large compared to the thermal velocity of the oxygen ion.

Mass spectra taken when the satellite is near perigee show that the major ion peaks are at mass numbers 1, 14, and 16 (amu), while minor ion peaks occur at mass numbers 2, 4, 8, 18, and occasionally 7, 15, and 20. The peak at mass number 1 is due to atomic hydrogen ions (H^+); at 14, to atomic nitrogen (N^+); and at 16, to atomic oxygen (O^+). The minor ion peaks (with their mass numbers) are tentatively identified as: deuterium (2), helium (4), doubly charged oxygen (8), either water vapor or O^{18} (18), neon (20), doubly charged nitrogen (7), and N^{15} (15). The latter two are seen only when there is a large abundance of N^{14}. Doubly charged ions appear at half their mass number, since the mass spectrometer measures the mass-to-charge ratio of the ion.

The predominant ion is O^+ up to the order of 1000 km, where the transition with H^+ occurs. The transition altitude appears to vary considerably with latitude, local time, and possibly other parameters. The abundance of N^+ varies from 5 to 30 percent of the O^+, and He^+ is seldom more than a few percent of the total ion density. Therefore, it appears that He^+ is not an important constituent in the ionosphere, at least at the time these data were recorded (December 1965 to March 1966).

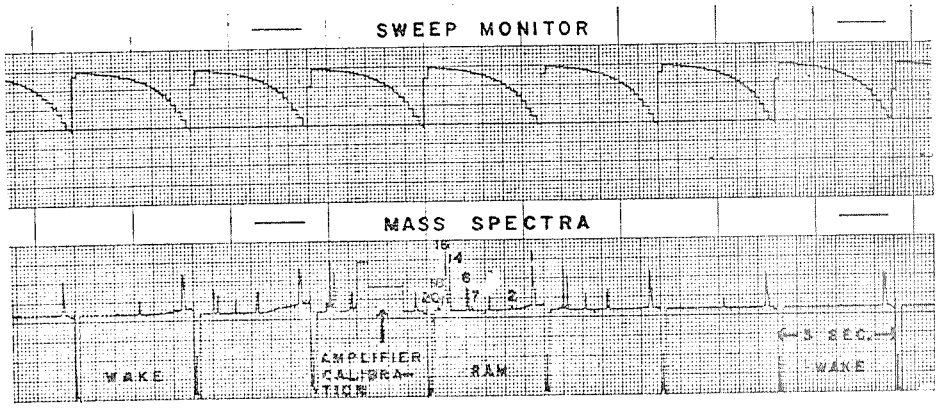

Fig. 1. Analog telemetry record for one spin period of the satellite, showing sweep monitor (top channel) and mass spectra (bottom channel). Ion peaks in mass spectrum are labeled in atomic mass units. Amplitudes are a logarithmic function of ion density. The sweep period is 3 seconds and the satellite spin period is approximately 20 seconds. Note absence of heavy mass ions (14, 16, and 18 amu) in wake positions. Internal 3-point amplifier calibration is shown on spectra channel.

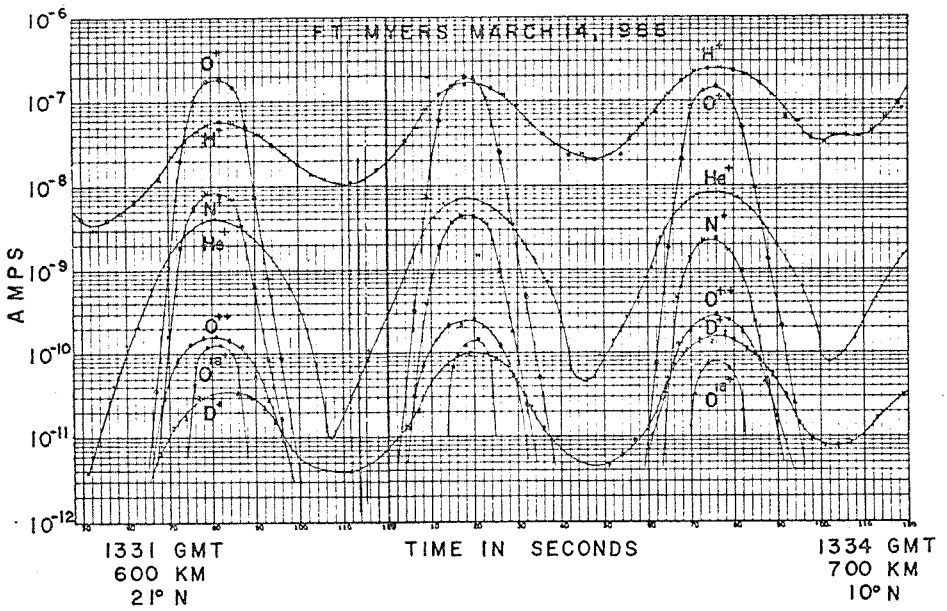

Fig. 2. Plot of peak amplitudes of successive mass spectra as a function of time, showing roll-modulation effect. Three satellite spin periods are evident. Labels of the abscissa (time in seconds) read from 50 to 120, in the left portion of the figure, and from 10 to 120 in the right portion.

The mass-2 ion peak is tentatively identified as deuterium. Its roll modulation amplitude lies between that of H^+ and He^+. The mass-2 peak could also be due to doubly charged helium ions, but from the roll modulation evidence it appears that it is more likely a mass-2 particle (deuterium). However, if the satellite potential (negative) is sufficiently large the roll modulation effect cannot be used to distinguish a singly charged particle from a doubly charged one of twice the mass. The possibility of the existence of an H^+_2 molecular hydrogen ion at altitudes above 500 km seems unlikely. The relative abundance of the mass-2 ion varies between 1 part in 10^4 and 1 part in 10^3 of the mass-1 ion. The ground level abundance of deuterium is 1.5 parts in 10^4 parts of hydrogen.

There is no evidence of a mass-3 ion peak. This peak would be due to the HD molecule or to He^3. The sensitivity limit of the mass spectrometer in this mass range is approximately 0.1 ion per cubic centimeter, which would represent an upper limit to the density of a mass-3 ion.

The mass-8 peak is tentatively identified as doubly charged oxygen. It is possible that this peak could be due also to He^+_2 (a mass-8 molecule), rather than to O^{++} (a mass-16 particle). or to a combination of the two. Since a mass-7 (N^{++}) peak is also observed where the mass-14 (N^+) peak is of sufficient intensity, that is, near perigee. it is possible that at least at low altitudes the mass-8 peak could be due mainly to O^{++}. The mass identification is not clear from the roll modulation because the whole modulation cycle is not visible above the sensitivity limit of the mass spectrometer. Near perigee, the ratio of the mass-8 to mass-16 ion peaks is of the order of 1 percent.

As mentioned above, mass-18 could be due to either water vapor or O^{18} ions, and both have been observed. For the first 2 months of the satellite life the mass-18 peak was always observed, but was not roll-modulated and had a gradually diminishing amplitude. Outgassing water vapor from the satellite is traveling at the velocity of the satellite and therefore would not be roll-modulated. After the water-vapor peak decreased sufficiently in amplitude, a roll-modulated mass-18 peak was observed, which is presumed to be the oxygen isotope at mass 18.

A mass-15 peak is also observed, presumably due to N^{15+}. The heavy isotopes of nitrogen and oxygen are found in the ionic state in the upper atmosphere in abundance ratios equal to or less than those at the earth's surface.

The mass-20 peak is thought to be due to neon. The abundance of neon at the earth's surface is three times that of helium. At 900 km the $20^+/He^+$ ratio was observed to be of the order of 1 percent.

Near apogee, the mass spectra exhibit peaks only at mass 1, 2, 4, and, at times, 8 amu. Again, these peaks presumably are due to ions of hydrogen, deuterium, helium, and O^{++} or He^+_2. The mass-18 peak was observed early in the life of the satellite, but was not roll-modulated and gradually disappeared with time as the outgassing of the satellite diminished. The predominant ion is H^+. The D^+/H^+ ratio is less than 2 parts in 10^4, and the He^+ abundance is a few tenths of 1 percent. The mass-8 peak appears in this altitude region where there is no mass 16 (O^+). Its abundance is of the order of that of the mass-2 ion.

The experiment described is still operating normally (September 1966).

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Notes

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28 October 1966

ION COMPOSITION MEASUREMENTS IN THE POLAR REGION FROM THE EXPLORER XXXI SATELLITE

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Presented at 49th Annual Meeting of American Geophysical Union, Washington, D. C., April 1968.

(P139) • JOHN H. HOFFMAN[1] (U. S. Naval Research Lab., Washington, D. C.), *Ion Composition Measurements in the Polar Region from the Explorer 31 Satellite.* Results from a magnetic mass spectrometer flown on the Explorer 31 satellite show that at certain times in the polar region, above the auroral zone, O^+ and N^+ ions become the dominant species at altitudes near apogee (3000 km). H^+ and He^+ ions are also present but of lesser abundance. In all other regions of the ionosphere H^+ is the dominant ion near apogee. He^+ is less than 1% of H^+, and O^+ and N^+ are not observed. The limit of detection for these heavy ion species is 1 ion/cm^3. The concentration of O^+ in this anomalous region, which lies between 75 and 85°N geomagnetic latitude, has been observed to be as high as 10^3 ions/cm^3. On each side there is a trough composed mainly of H^+ of the order of 10^2 ions/cm^3 on the low latitude side and less than 1 ion/cm^3 near the magnetic pole. To the south of the trough the ionosphere becomes almost entirely composed of H^+ with concentration of the order of 10^3 to 10^4 ions/cm^3 above 2000 km.

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

EXOSPHERIC COMPOSITION

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Exospheric composition. The composition of the Earth's atmosphere from ground level to 100 km is essentially constant because of vertical mixing. In the region above 100 km, the thermosphere, where there is very little vertical mixing, the distribution of gas molecules is governed by the laws of thermal diffusion. The atmosphere in this region is generally thought to be in diffusive equilibrium. The density of heavy molecules decreases more rapidly than that of light molecules or atoms, and gravitational separation of the various atmospheric gases occurs. From approximately 100 to about 400 km the temperature increases, but the region above this altitude becomes essentially isothermal. The upper portion of the thermosphere is called the exosphere and is the region in which the atmospheric gas is so rarefied that collisions between neutral particles can generally be neglected. The altitude of the base of the exosphere varies from 450 to 650 km during the solar cycle. From this region thermal energy molecules and atoms can escape from the Earth's atmosphere.

The composition of the neutral components in and below the exospheric region has been measured by C. A. Reber, using a magnetic mass spectrometer on the *Explorer 17* and *32* satellites. He finds that N_2 is predominant up to between 200 and 300 km, where atomic oxygen becomes the predominant constituent. The abundance of helium is approximately 1% and that of hydrogen slightly greater at 300 km. At higher altitudes a crossover with hydrogen occurs because of gravitational separation of the gas species. The actual crossover altitude is a function of temperature. *See* SPACE PROBES.

The region of the atmosphere that is partly ionized by solar radiation and sometimes by incoming high-energy particles is called the ionosphere. It begins below 100 km and extends out through the exosphere. It can be divided into two major regions, the bottomside and topside. The division between these two regions is the point of maximum ion concentration, called the F_2 maximum. The figure shows a nighttime distribution of ion concentration from 100 to 1000 km. This is a composite made up of data from two rocket flights, the lower portion (up to 230 km) being from data obtained by J. C. Holmes and coworkers in August, 1963, using a radio-frequency mass spectrometer, and the upper portion from data obtained by John H. Hoffman in January, 1964, using a magnetic mass spectrometer. In the F_2 maximum region the predominant ion species is O^+. Below the F_2 maximum the molecular ions, NO^+ and O_2^+, become the predominant constituents of the ionosphere. The dissociative recombination of these ions with electrons is the dominant loss mechanism in the ionosphere. *See* MASS SPECTROMETRY.

Above the F_2 maximum O^+ is the predominant ion. However, as can be seen in the figure, the H^+ and He^+ concentrations rise rapidly and eventually become the predominant species. At the time (1964) that the data of the figure were taken, the Sun was near its minimum-activity period. The temperatures of the ionosphere were low, and He^+ never became the predominant ion at any altitude. The transition from heavy to light ions proceeded directly from O^+ to H^+ and occurred at a very low altitude. At solar maximum it is expected from theoretical considerations that there will be a region of predominantly He^+ ions between the predominantly O^+ and H^+ regions and that the crossover altitudes will be higher.

Data obtained by means of a magnetic mass spectrometer on the *Explorer 31* satellite and reported by John H. Hoffman have shown that, at altitudes from 500 km (perigee) up to about 1000 km, the predominant ion is O^+, with a significant amount of N^+ also present (5–30% of the O^+). He^+ is detected, but its relative abundance is seldom more than 5% of the total ion concentration. Therefore, it appears that He^+ is not an important constituent in the ionosphere, at least at the time these data were recorded (December, 1965, to mid-1966). H^+ is present in varying amounts and increases with altitude until it becomes the dominant species. However, the crossover point with O^+ frequently occurs above 1000 km. This is contrary to the data obtained in the 1964 rocket flight, where the crossover occurs near 500 km. The conditions during the 1964 rocket flight were such as to produce a very low crossover altitude. The flight occurred at local midnight near the minimum of the solar cycle.

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Minor ions observed in this same region of the ionosphere are identified as D^+ (2 amu, or atomic mass units), O^{++} (8 amu), O^{18+} (18 amu), Ne^+ (20 amu), N^{++} (7 amu), and N^{15+} (15 amu). The latter two are observed only when there is a large abundance of N^{14}. Doubly charged ions appear at half their mass number, since the mass spectrometer measures the mass-to-charge ratio of the ion.

At 3000 km, the apogee of the *Explorer 31* orbit, the ionosphere consists almost entirely of H^+, with only a few tenths of 1% He^+. Helium also appears to play a very minor role in the upper ionosphere at the time near solar minimum. Other minor ions observed near apogee are D^+ (2 amu) and mass 8. The latter is sometimes observed above 2000 km, where there is no O^+ ion. Mass 8 in this region is believed to be He_2^+ and not O^{++}. The D^+/H^+ ratio is less than 2 parts in 10^4 (which is the ground-level value).

The average concentration of H^+ in the equatorial and mid-latitude regions near 3000 km is of the order of several thousand ions per cubic centimeter. Over the auroral and polar regions the concentration drops abruptly to the order of a hundred or less, and there are scattered regions in which the heavy ions, O^+ and N^+, become predominant. Also, the He^+ abundance rises somewhat in this region. The magnetic field lines from the polar region are connected to the geomagnetic tail. The light ions can quite easily be drained off along the field lines into the tail of the magnetosphere from this region, since here it requires only 0.5 ev of energy for H^+ and 2 ev for He^+ to escape.

H. A. Taylor has flown a radio-frequency mass spectrometer on the *OGO I* and *III* (Orbiting Geophysical Observatory) spacecraft and has found that the concentration of H^+ decreases slowly from several thousand ions per cubic centimeter at 2000 km to nearly a thousand ions at 30,000 km, where the concentration drops rather suddenly to less than 10 ions per cubic centimeter. This decrease may be thought of as a boundary of a belt of thermal ions in the magnetosphere. The H^+ to He^+ ratio is consistently 100 to 1 over most of this altitude range. At times, however, the outer boundary of this belt has been found to be as low as 8000 km. From Taylor's results there is some evidence that within this belt the distribution of ions is controlled along the lines of the geomagnetic field. The boundary level appears to have an inverse correlation with the magnetic activity index A_p.

There appear to be large variations in the composition and concentration of the gases in the exosphere during the course of the solar cycle and at times of strong magnetic storms. More data should be available in the near future that will help in an understanding of the spatial and temporal distributions and variations of these gases and the important processes controlling these variations. [J. H. HOFFMAN]

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Ion Mass Spectrometer on Explorer XXXI Satellite

JOHN H. HOFFMAN, MEMBER, IEEE

Abstract—A magnetic sector field mass spectrometer on the Explorer XXXI satellite, when calibrated in flight against electron concentration data from the Alouette II topside sounder satellite, measures the absolute concentrations of the various positive ion species in the ionosphere. The in-flight calibration is performed by comparing the total ion current measured by the mass spectrometer, corrected for internal discriminations, with the electron concentrations, first in regions of nearly pure H^+, then in regions of nearly pure O^+, to obtain calibration coefficients for each ion species. Data at 500 km show as many as ten different ion species in the ionosphere. Over the polar region, H^+ ions streaming upward at 10 to 15 km/s have been observed.

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I. DESCRIPTION OF INSTRUMENT

THE INSTRUMENT on the Explorer XXXI satellite designed to measure the composition of the earth's ionosphere is a $1\frac{1}{2}$-inch-radius, 60° sector field magnetic mass spectrometer. It scans the mass range from 1 to 20 amu and has a sensitivity to H^+ ions of the order of 1 ion per cm^3 and to O^+ ions of the order of 10 ions per cm^3.

Fig. 1 shows the entrance aperture (to the left), the magnet, and the electron multiplier housing of the mass spectrometer. The entrance aperture, which looks out the side of the satellite normal to the spin axis, consists of a 3-inch-diameter fine wire screen followed by an annular metal plate. The screen is commandable to either spacecraft ground potential or −6 volts with respect to the satellite skin potential. Field strength in the gap of the magnet in

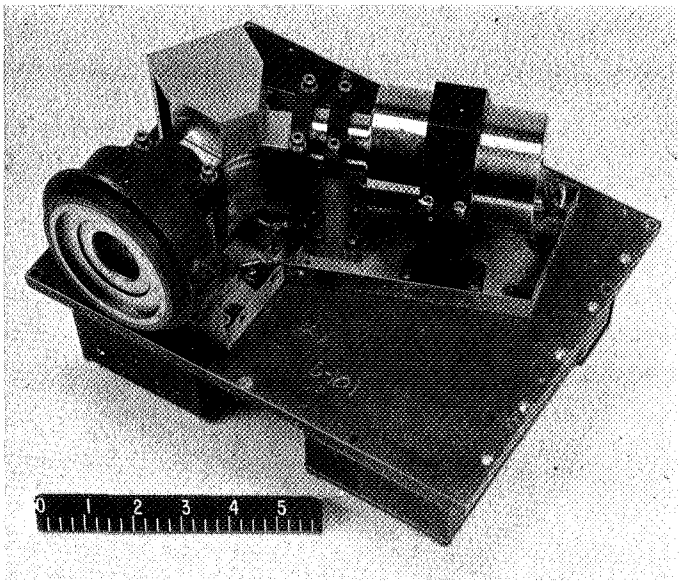

Fig. 1. Ion mass spectrometer. Complete package weighs $11\frac{3}{4}$ pounds and measures $10\frac{1}{2}$ by $8\frac{1}{2}$ by $6\frac{1}{2}$ inches. It consumes 1.6 watts of power. Electronics modules are housed below the base plate.

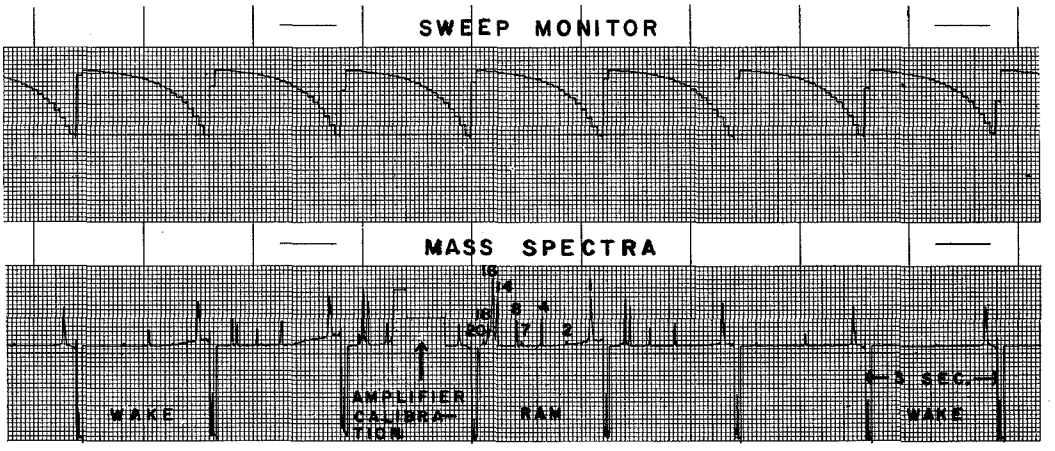

Fig. 2. Portion of analog telemeter record. Upper channel is sweep monitor. Lower channel is mass spectrum. Downward blips are markers to show recharge of high-voltage sweep circuit. Ion peaks are labeled in atomic mass units. Internal 3-point amplifier calibration operates every 100 seconds.

the analyzer section is 2200 gauss. A Bendix magnetic electron multiplier M308 serves as the ion detector.

The instrument operates as follows. The entire analyzer tube and magnet are swept through a negative high-voltage range (-4000 to -150 volts) causing ambient ions from the region in the vicinity of the entrance aperture to be drawn into the instrument and to be separated into their constituent species by the magnetic analyzer. The sweep period for the mass range 1 to 20 amu is 3 seconds. An electron multiplier and a solid-stage logarithmic electrometer amplifier, which has a current sensitivity range of 2×10^{-12} amperes for a voltage output range of 0 to 5 volts, comprise the output circuitry. Rise and fall times of the amplifier are of the order of 5 ms. The output voltage of the log amplifier plus a monitor of the high-voltage sweep are telemetered to earth. An internal calibrator in the log amplifier supplies currents of 10^{-11}, 10^{-9}, and 10^{-7} amperes to the amplifier input once each 100 seconds of operation. The resulting output voltages are used to generate constants in a calibration equation that relates volts, the output of the log amplifier, to input current. These constants are updated at each calibration cycle.

Fig. 2 shows a sample analog telemetry record with the sweep voltage on the top channel and the mass spectrum below. The position of a peak in the spectrum determines the ion species being measured. The amplitude of the peak is proportional to the logarithm of the ion current detected by the electron multiplier for that ion species. This ion current is a function of the concentration of that species in the vicinity of the entrance aperture of the mass spectrometer. However, the concentration of ions in this region is dependent on the satellite attitude, velocity, and potential and has a complex relation to the ambient ion concentration. An in-flight calibration, which is described below, is necessary to obtain absolute ion concentrations.

In Fig. 2, a pass taken near perigee (500 km), peaks due to ions of hydrogen (1 amu), deuterium (2), helium (4), doubly charged nitrogen (7), doubly charged oxygen (8), nitrogen

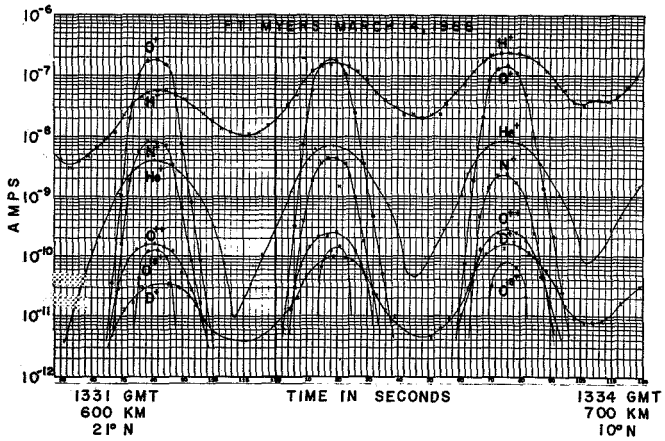

Fig. 3. Roll modulation of ion peak amplitudes. Peak amplitude versus time.

(14), oxygen (16), water vapor or O^{18} (18), and neon (20) are observed in the RAM position. For the first two months of life of the satellite the mass 18 peak was principally due to water vapor. The amplitude gradually decreased while the roll modulation (described below) increased leaving a residual peak due to O^{18}, the O^{18}/O^{16} ratio being about that of normal ground level oxygen. Occasionally a mass 15 peak from N^{15} is observed, the N^{15}/N^{14} ratio being about that of normal nitrogen. The mass 8 peak may also consist partly of He_2^+; but at low altitudes, where O^+ is the dominant constituent, it is likely that the mass 8 peak consists mainly of O^{++}, formed by photoionization of O^+. At the WAKE position, only peaks at mass 1 and 4 amu are visible and these are reduced in amplitude from the RAM condition.

At altitudes near apogee (3000 km) at mid to low latitudes the mass spectra show only peaks at 1, 2, 4, and occasionally 8 amu. These are identified as hydrogen (1), deuterium (2), helium (4), and He_2^+ (8). In this region no O^+ is observed so the mass 8 peak is probably due to the He_2^+ ion.

The satellite is oriented so that its spin axis is maintained normal to the orbital plane (a cartwheel orbit). Thus, the mass spectrometer entrance aperture on the side of the satellite alternately points along the satellite velocity vector, the RAM condition, and opposite to it, the WAKE condition.

Since the satellite is traveling at a speed greater than the mean velocity of the ambient hydrogen ion, the RAM and WAKE conditions are exhibited as a roll modulation in the ion peak amplitudes. The satellite spin period varies from 7 to 12 sweep periods. Fig. 2 shows one roll modulation cycle. The mass 1 peak is relatively constant while the heavy ion peaks (mass 14, 16, 18) are absent in nearly half of the spectra.

Fig. 3 is a plot of the peak amplitudes of successive mass spectra as a function of time. The roll modulation is quite evident and it should be noted that its amplitude is a strong function of ion mass. For H^+ it is about 1 order of magnitude; for He^+, $2\frac{1}{2}$ orders of magnitude; and for O^+, more than 5 orders of magnitude.

II. Calibration of Mass Spectrometer

An ion mass spectrometer measures the relative abundances of the ions it samples from the ionosphere but can be calibrated, as is described below, to give absolute ion concentrations. Several factors cause the spectrometer to discriminate against ions of heavy mass. First, the instrument scans the mass spectrum by varying the ion accelerating voltage in an exponential manner from 4000 to 1500 volts. Low-mass ions are measured near the high-voltage end of the sweep where the instrument has a higher transmission factor than at the low-voltage/high-mass end. This phenomenon is known as the voltage effect. Second, light mass ions, being more mobile than heavy mass ions, are collected from a larger volume. Hence, a larger light mass ion current is measured for equal concentrations of light and heavy mass ions. Third, the roll modulation amplitude has been shown above to be a strong function of ion mass. It is therefore most practical to measure the ion abundance ratios only in the RAM condition, when the sensitivity for each constituent is a maximum.

In order to correct for the mass discriminations discussed above several methods of calibration of the mass spectrometer were employed. The mass discrimination of the mass spectrometer due to the voltage scan mode of operation was measured in the laboratory by determining the ratios of gases in standard mixtures which have been calibrated by another mass spectrometer using magnetic scan. Ion currents (amperes) are converted into ion concentrations by multiplying by a constant of the order of 10^{10}.

In-flight calibration for the sampling efficiency of the various ion species from the plasma was performed by comparing the total ion current (the sum of all the peaks) with electron density data from the Alouette II topside sounder satellite. The Alouette II and Explorer XXXI satellites were launched piggyback into similar orbits. The time separation between passage of the two satellites over a given latitude (less than 30 minutes for the passes used in this calibration) is assumed to be small compared to variations in the ionosphere at that latitude. Hence, both satellites measure the same ionosphere and the data used in the comparisons are considered to be simultaneous data. Comparisons were first made in regions where the ionosphere consisted of greater than 95 percent H^+ ions (the remainder being He^+ and D^+). A plot of the calibration factor (ratio of electron concentration to ion concentration) against H^+ concentration is shown in Fig. 4. Data are plotted over a range of concentration from 9×10^3 (the maximum H^+ concentration that has been observed) to 1×10^3 ions per cm^3. A linear relationship is seen to exist. The fact that the calibration coefficient is not constant may be due to the variation in plasma sheath thickness around the satellite as the ion concentration changes. Thus, a direct calibration of the absolute sensitivity of the mass spectrometer to H^+ was obtained. Next, a similar calibration was made for O^+ using ionospheric regions that were greater than 90 percent O^+. In this case the calibration for H^+ was incorporated into the calculation. The concentration for the

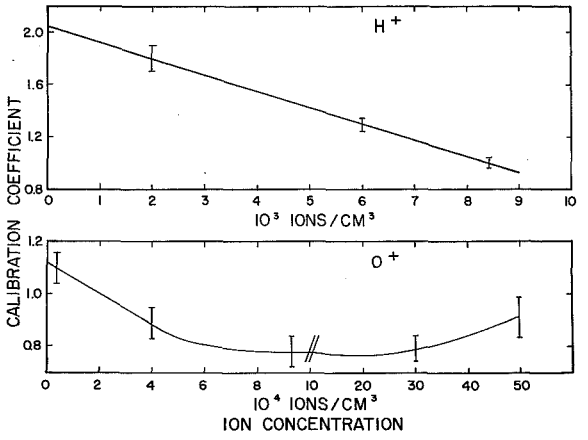

Fig. 4. Calibration coefficients. Ratio of Alouette II electron density to H^+ and O^+ concentrations versus ion concentration. Note scale change in abscissa of O^+ curve.

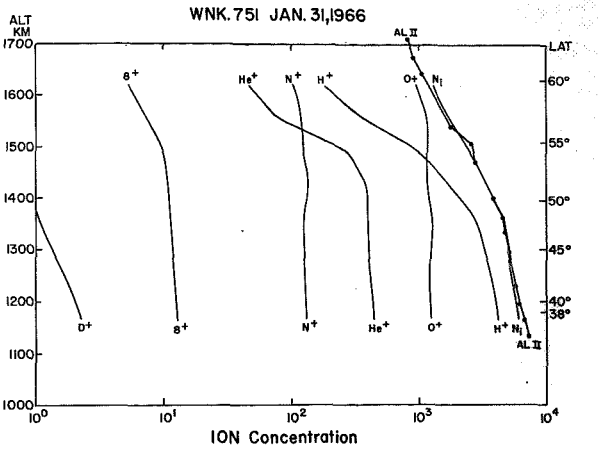

Fig. 5. Pass showing comparison of ion data with Alouette II electron concentrations. Concentrations are plotted as a function of both altitude and latitude.

O^+ calibration (Fig. 4) ranges from 5×10^5 to 1×10^2 ions per cm^3. A linear relationship exists at lower concentrations but a saturation effect and reversal set in above 10^5. At low concentrations (below 10^3) the sheath has little effect on the sampling volume and hence the calibration coefficient. The absolute sensitivity of the mass spectrometer for the other ions was obtained by interpolation from these data. Obviously, the accuracy of sensitivity to the minor constituents is less than that for H^+ and O^+, but since the concentrations of these species generally lie below 10^3 (except for N^+ whose mass and mobility is close to O^+) the calibration coefficients are almost constants. Most of the passes used for this calibration procedure were different from the passes selected for comparison with the other experiments on Explorer XXXI, the results of which are presented in the paper entitled "Comparison of Results of Explorer XXXI Direct Measurement Probes" [1] which appears elsewhere in this issue. Hence, the comparisons in the latter paper show the degree of agreement between the results obtained by applying the calibrations discussed here and the results obtained by the other experiments in this program. This agreement is generally to about 10 percent.

A typical example of the result of this in-flight calibration procedure is shown in Fig. 5. The absolute concentration of each ion species is plotted against satellite altitude. The Alouette II topside sounder data for the same pass are also shown. Agreement between the total ion concentration N_i as determined by the sum of the individual ion species concentrations, and the electron density is of the order of 10 percent. In this pass the ion composition changes from 75 percent O^+ at 1620 km to 66 percent H^+ at 1170 km. Thus it can be seen that the mass spectrometer is capable of making absolute ion concentration measurements to the order of 10 percent when calibrated against simultaneous electron concentration data such as obtained from the topside sounder.

The mass spectrometer has a sensitivity to H^+ ions of the order of 1 ion per cm^3 and to O^+ ions of 10 ions per cm^3. The Alouette II topside sounder data when analyzed by the standard method [4] can give electron concentration data

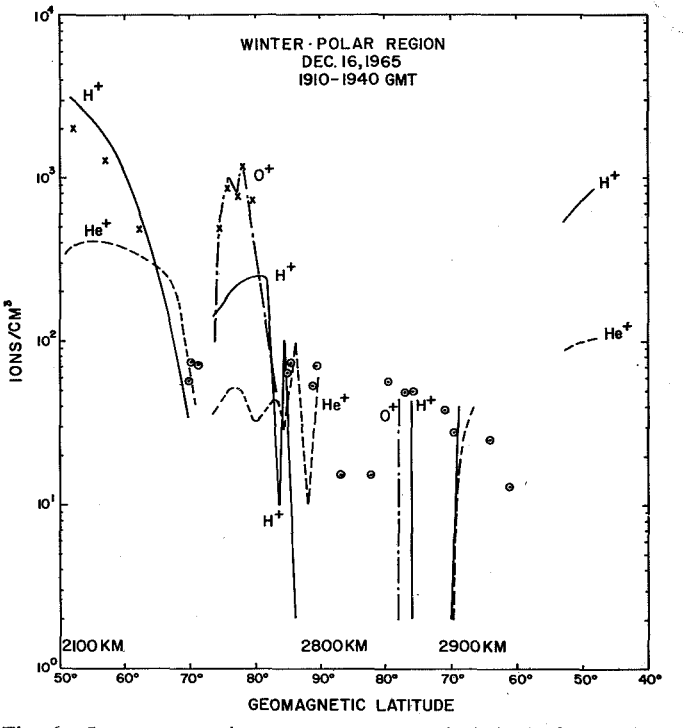

Fig. 6. Ion concentrations versus geomagnetic latitude for northern polar region. Crosses are Alouette II data reduced by standard method. Circles are Alouette II data by Hagg method. In region around 80° to 85° N H^+ ions have an upward drift velocity of 10 to 15 km/s. N^+ is also observed at a concentration of 6 percent of O^+ (not shown in figure).

as low as several hundred electrons per cm^3. For concentrations below this level the beat frequency method due to Hagg [2] must be employed. Since the mass spectrometer can also measure concentrations in this range, a comparison was made with the Alouette data for a high altitude pass #209 that traversed the northern polar region. The results are shown in Fig. 6. This pass shows a region of highly variable ion concentration. The Alouette II data are given as crosses for the standard method of reduction and as circles for the Hagg data. Above a concentration of 500 ions per cm^3 the agreement is to within 20 percent except at the ex-

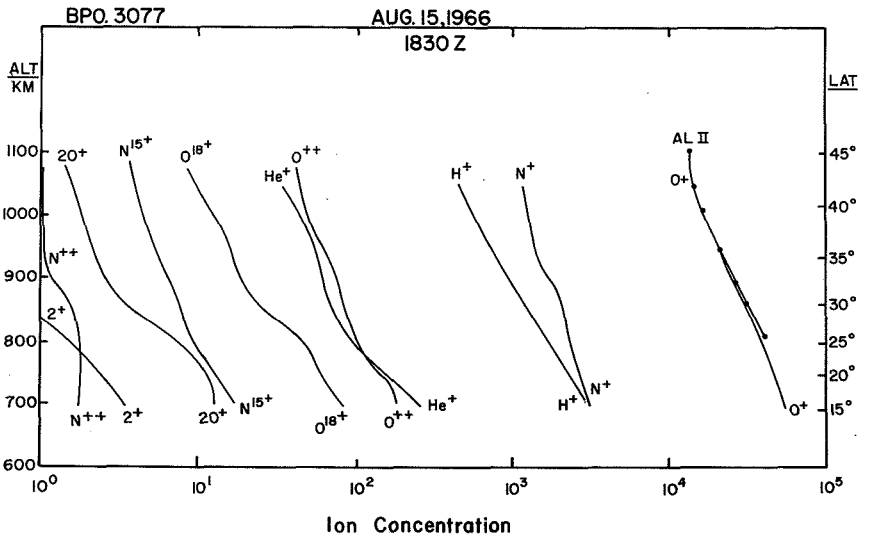

Fig. 7. Typical low-altitude data showing ion concentrations versus altitude and latitude. Ten different ion species are observed. Alouette II electron concentrations are also given.

treme left in the figure (where one point differs by 30 percent and one by 40 percent) for both a predominantly H^+ ionosphere, and an O^+ region near the center of Fig. 6. For concentrations between 30 and 100 ions per cm^3 at 70° to the left and again from 85° to 90°, regions where He^+ is predominant, and to the right at 80° to 75° (H^+ and O^+ regions, highly structured) the agreement with the Hagg results is also to the order of 20 percent. Below 30 ions per cm^3 the mass spectrometer data lie well below the Hagg results. In fact, in part of the region over the pole, the mass spectrometer shows no ions (less than 1 ion per cm^3) while the Hagg method shows concentrations of 15 to 30 electrons per cm^3. In this region the spacecraft potential has gone sufficiently positive, as determined by the ion trap on the satellite, to repel all ions from the satellite. Apparently it requires electron concentrations of the order of 30 electrons per cm^3 to sufficiently neutralize the spacecraft potential, made positive by photoemission, to allow the mass spectrometer to collect any ions at all from the region around the spacecraft. However, when this condition does exist, that the spacecraft potential is near zero (within 1 or 2 volts), the mass spectrometer results agree reasonably well with the topside sounder results down to a concentration of 30 ions per cm^3 as shown by this example.

III. Sample Results

At near satellite apogee (3000 km) and at mid to low latitudes the ionosphere generally consists of the order of 99 percent H^+, the remainder being He^+ and D^+. Fig. 6, however, shows an example of a region of the polar ionosphere above 70° N geomagnetic latitude where O^+ is the dominant species at 2800 km. The ionosphere exhibits a considerable amount of structure here. N^+ is about 6 percent of O^+ and follows the same distribution but is not shown on the graph. On either side of this structured region there is a trough, at 70° N and over the pole. To the south of the trough, H^+ becomes the dominant species and O^+ is not observed. There is evidence from the phase difference of the maxima in the roll modulation curves in this structured region that H^+ ions are flowing upward with a velocity of 10 to 15 km/s [3]. The O^+ scale height here, from the Alouette II N-H profile, is 500 km. Since O^+ is the dominant constituent, and the field lines are not closed in this region, an upward flow of H^+ ions would be expected, as is observed.

Fig. 7 shows a typical midlatitude low-altitude pass. Ten different ion species are observed, the concentrations of which are plotted as a function of both altitude and latitude. Alouette II electron concentrations are also shown. H^+ plays a very minor role at this time—midday, summer. The light ion concentrations are increasing with decreasing latitude and altitude. In a diffusive equilibrium situation the minor light ion concentrations should decrease with decreasing altitude. Thus it appears that the latitude effect here is stronger than the change with altitude.

Acknowledgment

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Comparison of Results of Explorer XXXI Direct Measurement Probes

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Abstract—Intercomparison measurements of the major ionospheric parameters of ion and electron density and temperature and ionic species made by direct measurement probes on the Explorer XXXI satellite are presented. Plasma density results are compared with simultaneous data from the Alouette II satellite. Probe results are from the following experiments: planar ion trap, planar electron trap, cylindrical electrostatic probes, high resolution magnetic ion mass spectrometer, planar Langmuir plate, and spherical ion probe.

The plasma densities measured by the various probes generally agree with simultaneous Alouette II sounder values to within 20 percent. Electron temperatures measured by three different types of probes generally agree within 10 percent. Ion composition measurements by the planar ion trap and spherical probe show good agreement with the high resolution magnetic mass spectrometer. Ion temperature measurements from the ion trap are consistently higher than spherical ion probe results.

Introduction

THE EXPLORER XXXI Satellite (Direct Measurements Explorer-A) was launched along with the Alouette II Topside Sounder Satellite on November 29, 1965, into an 80° prograde polar orbit with a perigee of 500 km and an apogee of 3000 km. The combined launch of the two spacecraft is called the ISIS-X project.

An important objective of the ISIS-X mission was the simultaneous measurement of ionospheric parameters by direct measurement probes and electron density profiles measured by the topside sounder experiment on Alouette II. The close proximity of the two satellites provided an excellent opportunity for such simultaneous data coverage for several months after launch. The orbital separation was about 105 seconds (about 800 km) two months after launch.

Explorer XXXI was instrumented with direct measurement probes which provided measurements of the major ionospheric parameters through different techniques. The experiment complement, measured parameters pertinent to the comparison, nominal data accuracies, and principal investigators are as follows:

1) Planar ion trap—ion density (±10 percent), temperature (±150°K), and composition; J. L. Donley.

2) Planar electron trap—electron density (±20 percent) and temperature (±200°K); J. L. Donley.

3) Cylindrical electrostatic probes—electron density (±10 percent) and temperature (±150°K); L. H. Brace and J. A. Findlay.

4) Magnetic ion mass spectrometer—ion density (±10 percent) and composition; J. H. Hoffman.

5) Planar Langmuir plate—electron temperature (±100°K); A. P. Willmore and G. L. Wrenn.

6) Spherical ion probe—ion density (±2 percent), temperature (±200°K), and composition; A. P. Willmore and G. L. Wrenn.

The accuracies are mainly indicative of data scaling error bounds and do not reflect a relationship between the measured quantity and the absolute value of the parameter under study.

The experimental implementation and data analysis procedures have been described in separate papers included in this issue.

Comparison Passes

For the purpose of data intercomparison the passes listed in Table I were selected for detailed study. These passes were selected on the basis that all experiments were operating satisfactorily and good aspect data and simultaneous Alouette II sounder data were available. For the passes selected the maximum in-orbit separation time of the satellites was less than 105 seconds, and regions of rapidly varying ionospheric conditions have been avoided. A wide variety of geographic locations and plasma density conditions are covered. The spacecraft was in sunlight for all passes. The northern auroral regions, which represent a large percentage of data coverage, have been excluded from this initial comparison study since such passes were at apogee altitudes and consequently very low plasma densities (about 10^2/cc) which are below the sensitivity threshold of some experiments were encountered.

Data Comparison Results

Plasma Density

The results of the comparison of electron and ion density values are summarized in Fig. 1. Results are shown as the ratio of the Explorer XXXI probe measurements to the Alouette II sounder values as a function of plasma density. The sounder data were chosen to coincide in location with the Explorer XXXI values. Since the maximum time separation of the two satellites during this comparison is less than two minutes and regions of rapidly varying ionospheric conditions have been excluded, it is felt that the time-shifted sounder data provide a suitable value for local electron density at the satellite altitude to serve as a comparison standard. Alouette II ionogram data used have been scaled

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TABLE I

DETAILS OF COMPARISON PASSES

Station	Pass	Date	Universal Time		Height (km)		Latitude (Degrees)		Longitude (Degrees)	
			Start	End	Start	End	Start	End	Start	End
Kano (KNO)	368	30DEC65	0449	0458	1555	2120	2.2	27.7	12.3	15.0
Orroral (RAL)	546	14JAN66	0631	0638	709	538	−26.1	−53.1	144.6	151.6
Winkfield (WNK)	550	14JAN66	1411	1418	2224	1797	55.5	36.9	9.0	14.6
Blossom Point (BPO)	730	29JAN66	1842	1849	1359	935	44.6	21.1	−80.8	−76.4
Santiago (SNT)	730	29JAN66	1900	1905	537	525	−20.9	−46.9	−71.3	−67.6

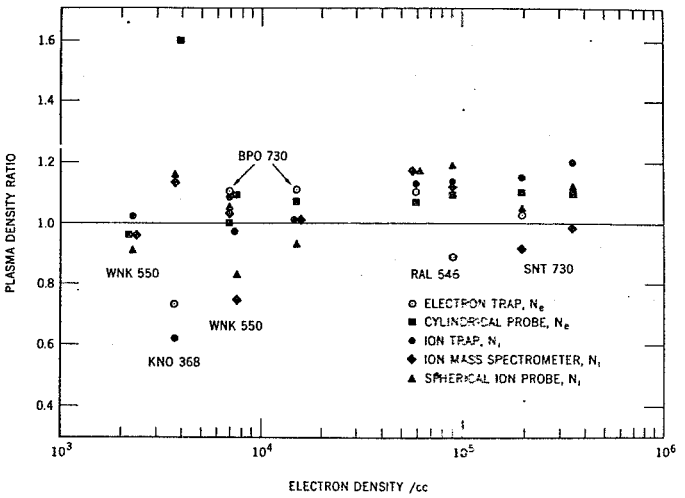

Fig. 1. Comparison of Explorer XXXI plasma density measurements with simultaneous Alouette II topside sounder electron density results. The ratio of the Explorer XXXI probe measurements to the Alouette II values (a value of 1.0 indicates exact agreement) is plotted as a function of plasma density.

by the Defence Research Telecommunications Establishment in Ottawa, Canada, and the Radio and Space Research Station in Slough, England. In cases where values furnished by the two sources have been in disagreement, a mean value has been employed for comparison purposes. The maximum scaling disagreement noted for the Alouette II data was about 10 percent.

The range of values of plasma density in the comparison passes is from 2×10^3 to 4×10^5 el/cc. For the RAL 546 and SNT 730 passes, which represent low-altitude high-density dominant oxygen-ion conditions, all probe results are within 20 percent of the Alouette values. For the passes with less than 2×10^4 el/cc, errors of up to 60 percent are noted.

The results of the spherical ion probe density measurements on the WNK 550 pass are lower than Alouette II densities due to insensitivity to oxygen (O^+) ions. The limiting sensitivity on O^+ measurements for the ion probe is approximately 300/cc. The ion mass spectrometer indicates that for the WNK 550 pass the O^+ density is in the range 200 to 500/cc. The ion probe results indicate no O^+ on this pass and are thus lower than Alouette II values. On the KNO 368, which consists of essentially all hydrogen (H^+) ions, the probe results are in better agreement with Alouette values. It thus appears that the spherical ion probe (as implemented on Explorer XXXI) yields valid plasma density values provided the number density of O^+ ions is negligibly small (H^+ is the dominant species), or is large compared to the O^+ sensitivity threshold.

The cylindrical electrostatic probe experiment yields electron density values in good agreement with Alouette on all passes except KNO 368. This pass yielded a value 60 percent high. Also on KNO 368, values of ion and electron density from the ion trap and electron trap are up to 40 percent low. No explanation has been found for these discrepancies. Otherwise, good agreement is obtained on the other passes. Sufficient comparisons have not yet been made to ascertain the statistical significance of the occurrence of passes which show large discrepancies in plasma density results for the ion and electron trap experiments and the cylindrical probe.

Values of ion density obtained by the magnetic ion mass spectrometer show very good agreement with Alouette values with the exception of one measurement on the WNK 550 pass which is 25 percent low. Since a large number of Alouette II density values have been used to ascertain the effective collection volume of the mass spectrometer as a function of plasma density and ionic species [1], it is expected that the spectrometer results are a valid measure of the local ion density.

Values of electron density from the electron trap are not

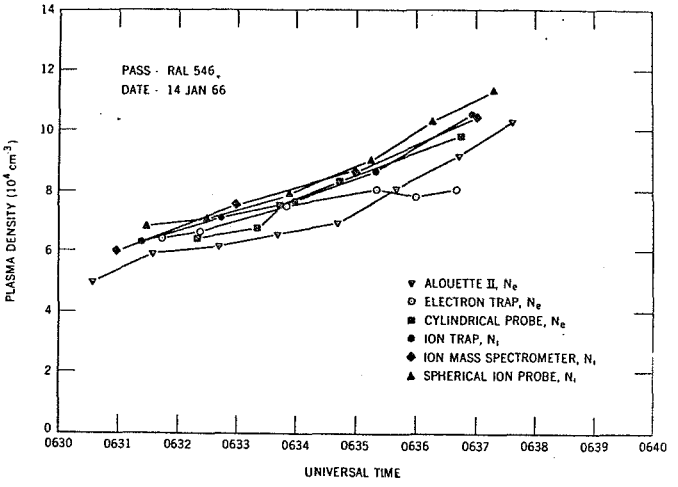

Fig. 2. Plasma density measurements for the RAL 546 pass on January 14, 1966. Individual data points are connected by straight lines.

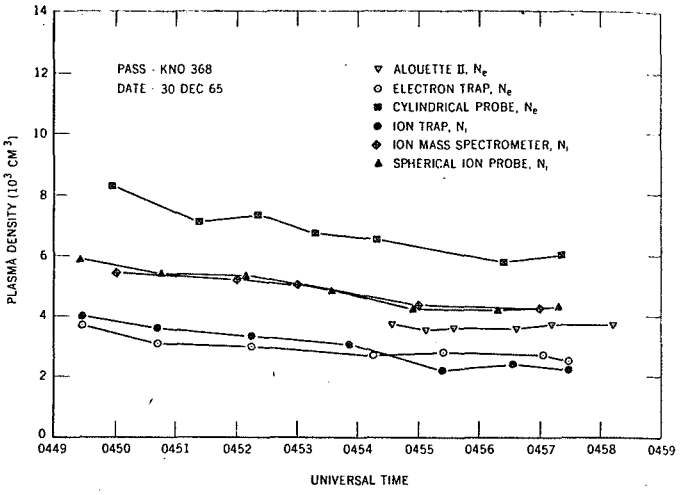

Fig. 3. Plasma density measurements for the KNO 368 pass on December 30, 1965. Values from the cylindrical probe are up to 60 percent high and values from the ion and electron trap are up to 40 percent low with respect to Alouette II density measurements.

TABLE II

ELECTRON TEMPERATURE COMPARISONS

Station	Pass	Universal Time	Electron Trap °K	Cylindrical Probe		Planar Langmuir Plate	
				#1°K	#2°K	Forward °K	Nonforward °K
Kano	368	0450:30	3300	3250	—	3600	3470
		0452:30	3200	3150	3250	3110	2910
		0454:15	3250	3150	3300	3370	3350
		0456:15	3350	3200	3350	3320	3360
Orroral	546	0631:45	3250	3500	—	2680	—
		0633:45	3150	3500	—	2880	2950
		0637:00	2650	3400	—	2480	2780
Winkfield	550	1412:00	4250	3950	—	3450	—
		1413:45	4200	3900	—	3270	3580
		1416:00	4100	3850	—	3890	—
		1417:15	4050	3750	—	3680	3060
Blossom Point	730	1843:00	3900	3900	3600	3390	3820
		1845:15	3750	3800	3550	2970	3790
		1847:00	3600	3800	3550	2930	3730
		1848:15	3650	3750	—	3400	—
Santiago	730	1901:45	1600	1500	—	1350	—
		1902:45	1600	2200	—	1560	—
		1904:00	1850	2400	—	1900	—

vailable for the WNK 550 pass since the sensor was illuminated by the sun when in the forward direction. Density values less than about 10^4/cc cannot be obtained reliably hen the sensor is illuminated [2].

Fig. 2 shows the detailed plasma density comparisons for the RAL 546 pass versus universal time. O^+ is the dominant onstituent for this pass. All Explorer XXXI probes show greement with Alouette II density values although in general they are 10 to 15 percent above the Alouette II alues. Individual data points are connected by straight nes.

Fig. 3 shows the comparisons for the KNO 368 pass. This pass shows the largest departures from Alouette data values for any of the comparison passes. Even though this large error is present in the cylindrical electrostatic probe data and the ion and electron trap data, the data from each experiment yield the same relative variations.

Electron Temperature

The electron temperature comparisons are shown in Table II. Values from the electron trap experiment were obtained when the sensor was oriented in the forward direction on all passes except WNK 550. These values were at angles of attack of 60° to 90° since forward looking values were distorted due to solar illumination of the sensor. Cylindrical electrostatic probe values are 30 second aver-

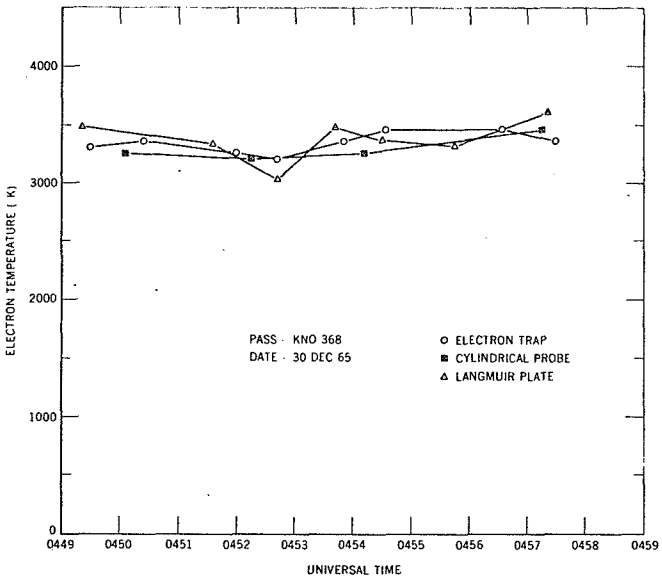

Fig. 4. Electron temperature measurements for the KNO 368 pass on December 30, 1965. For this pass, mean values for the two cylindrical probes and the forward and nonforward Langmuir plate results are shown since the individual differences were within the measurement error bounds.

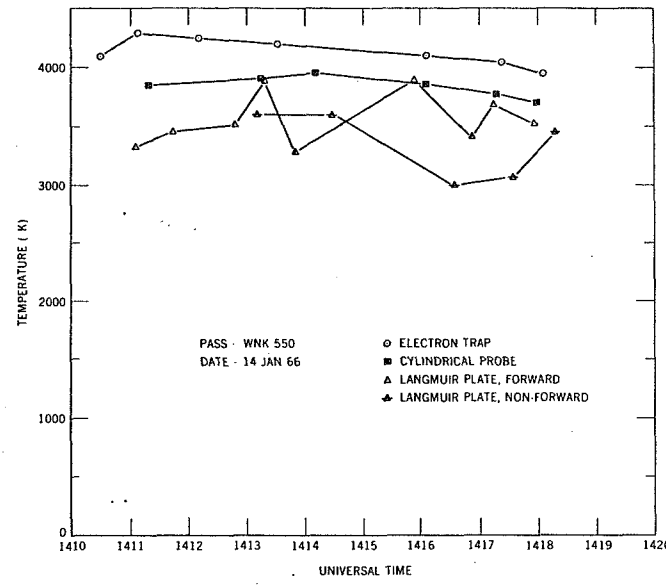

Fig. 5. Electron temperature measurements for the WNK 550 pass on January 14, 1966. The greatest differences between various probe results are evident on this pass.

ages, corresponding to one and a half satellite roll periods. Values for the two identical probes are shown only when there is a statistically significant difference between them. Planar Langmuir plate values are given for both forward and nonforward directions.

Excellent agreement in electron temperature was obtained on the KNO 368 pass. As illustrated in Fig. 4. individual probe results are all within 10 percent of each other.

On the other comparison passes deviations of up to 20 percent from the mean measured electron temperature are evident. On the SNT 730 pass, cylindrical probe results agree with other measurements at the beginning of the pass but show significantly higher values at the middle and end of the pass. On RAL 546 the cylindrical probe is also higher than other values. On WNK 550 the electron trap values are higher than other results. Examination of the planar Langmuir plate results indicates significant differences between forward and nonforward values particularly on the BPO 730 pass. The same pass has the largest difference between the two cylindrical probes. This result suggests the presence of anisotropies in the electron energy distribution. A possible source of the anisotropy would be orientation with respect to the local magnetic field; however, the BPO 730 pass does not represent a unique position or orientation compared with the other comparison passes. Therefore any anisotropy present in BPO 730 may be unique to the time of this pass.

The data from the WNK 550 pass, Fig. 5 shows the largest difference between probe results for any of the comparison passes. Differences of up to about 1000°K are present between the results of the electron trap and the Langmuir plate. Also significant anisotropy is present in the planar Langmuir plate results at the end of the pass.

If the passes included in this comparison are truly typical of the probe results, the cylindrical probe is typically above and the Langmuir plate is typically below the mean measured temperature. The maximum deviation from the mean is about 20 percent.

Ion Temperature

Measurements of ion temperature were made by the planar ion trap and the spherical ion probe. The results of the planar ion trap experiment require detailed satellite aspect data. The spherical probe is essentially omnidirectional and aspect information is not essential. The only restriction is that the probe be free of the satellite wake. For the comparison passes the aspect data are believed to be correct with a maximum error not greater than $\pm 5°$.

Of the five comparison passes, the RAL 546 and SNT 730 passes have O^+ as the dominant ionic constituent, KNO 368 and WNK 550 have H^+ dominant, and BPO 730 has O^+ major with significant amounts of H^+. Table III shows the ion temperature results. In addition to the H^+ and O^+ temperatures, the mean electron temperature results discussed in the previous section are included for comparison.

On the KNO 368 pass the ion-trap H^+ temperatures are consistently about 500°K higher than results from the spherical probe, as shown in Fig. 6. The H^+ temperatures from the ion trap are the result of excellent curve fits to the raw data showing deviations of less than ± 50°K. Both experiments yield ion temperatures which are considerably below the measured electron temperatures.

The other dominant H^+ pass is WNK 550. The ion-trap values are again much higher than the spherical probe results (Table III). Within the error bounds the ion-trap values are approximately equal to the electron temperature while the spherical probe results are about 1000°K lower. The larger than nominal error limits indicated on the trap results are indicative of uncertainties in the curve fitting results. Sources of ion-trap uncertainties are aspect errors

TABLE III
ION TEMPERATURE RESULTS

Station	Pass	Time	Ion Trap		Spherical Probe		Mean T_e(°K)
			T_{H^+} (°K)	T_{O^+} (°K)	T_{H^+} (°K)	T_{O^+} (°K)	
Kano	368	0449:30	2580	—	2090	—	—
		0452:15	2420	—	1900	—	3250
		0454:14	2450	—	2130	—	3300
		0456:15	2480	—	1780	—	3350
Orroral	546	0631:30	—	2650	—	1430	—
		0633:15	—	2720	—	1560	3150
		0635:00	—	2220	—	1420	3050
		0637:00	—	1850	—	1200	2850
Winkfield	550	1411:45	3800±550	—	3000	—	3850
		1413:45	4100±550	—	3000	—	3750
		1416:00	4150±200	—	2450	—	3850
		1417:30	3800±200	—	2400	—	3650
Blossom Point	730	1843:15	3100±350	3250	2650	—	3750
		1844:45	3250	3150	2100	—	3700
		1846:00	3000	3050	2200	—	3650
		1848:15	3050	2750	1900	—	3600
Santiago	730	1901:15	—	1600	—	1050	1300
		1902:15	—	1530	—	1150	1550
		1903:15	—	1670	—	1120	1700
		1903:40	—	1800	—	1030	1800

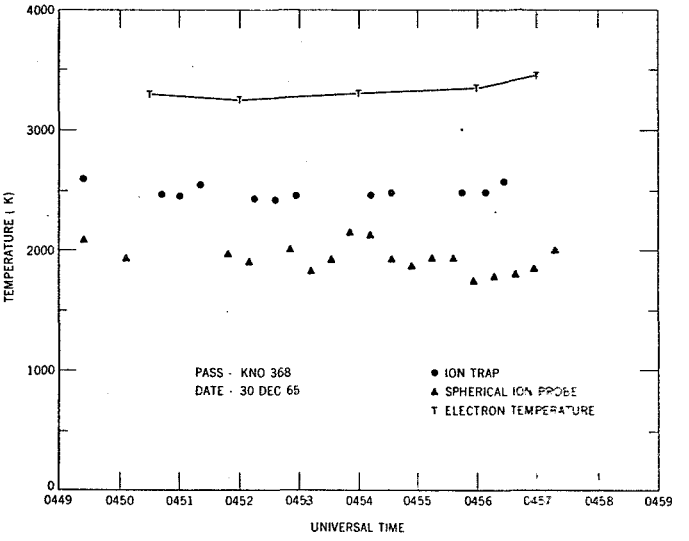

Fig. 6. Hydrogen ion temperature measurements for the KNO 368 pass. Mean electron temperature is also shown.

ven though no greater than ±5 degrees), presence of minor constituents particularly He^+, and solar illumination of the sensor causing secondary emission current which presents an error signal component. Additional comparisons of H^+ temperatures are required to resolve differences, since the values from either technique may be orrect.

The dominant O^+ passes, RAL 546 and SNT 730, also show ion-trap temperatures above those of the spherical robe (see Figs. 7 and 8). The difference ranges from about 00°K up to 1200°K. On SNT 730 the ion-trap values are close to the measured electron temperature while the spherical probe results are closer to the neutral gas temperature. Backscatter radar results from Jicamarca (magnetic equation) in December, 1965, show ion and electron temperatures equal at altitudes above 350 km [3]. Results from Arecibo radar (30°N magnetic) in the summer of 1965 show afternoon electron temperatures of 1600 to 1900°K and ion temperatures of 1600 to 1700°K at altitudes of 500 to 550 km [4]. The SNT 730 pass is at an altitude of about 530 km and at latitudes of from about −15° to −30° magnetic in the summer hemisphere. The ion-trap temperature results are in agreement with the radar data. The measured electron temperatures from the electron trap and Langmuir plate are also in agreement with these radar data.

The RAL 546 pass contains midlatitude (−37° to −57°

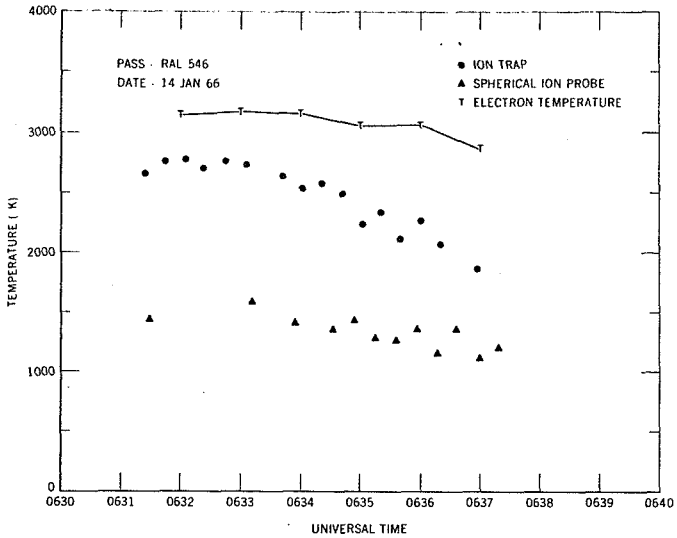

Fig. 7. Oxygen ion temperature measurements for the RAL 546 pass.

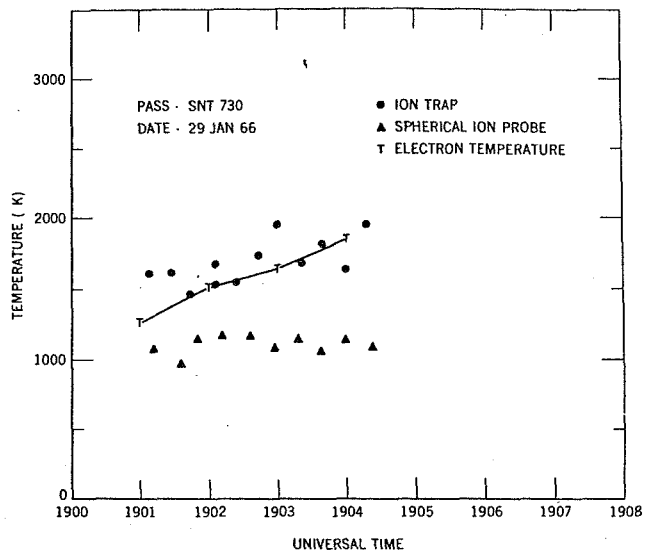

Fig. 8. Oxygen ion temperature measurements for the SNT 730 pass. The scatter in ion-trap values is most likely due to errors in satellite attitude data.

magnetic) southern hemisphere summer data. Midlatitude data from the Millstone Hill radar (58°N magnetic) at solar minimum in summer 1964 show an electron temperature of about 2600°K and ion temperature of about 1550°K at an altitude of 550 km [5]. Probe measurements taken at 0637 UT (−57° magnetic, 550 km) on the RAL 546 pass give a mean electron temperature of 2850°K which is in agreement with the Millstone radar data. At this same time the ion temperature results are 1850°K from the ion trap and about 1200°K from the spherical probe. These results are not in direct agreement with radar data; however the ratio of measured electron to ion temperature for the ion trap (1.5) is in closer agreement with the radar results (1.7) than the spherical probe result (2.4).

On the BPO 730 pass significant amounts of H^+ ions are present. As indicated in Table III, the spherical probe measurements are for H^+ ions only while the ion trap shows results for both H^+ and O^+ ions. The ion-trap results indicate in general that the H^+ and O^+ ion temperatures are equal. The trap results are again significantly higher than the results of the spherical probe. The ratio of electron to ion temperature for this pass is about 1.2 for the ion trap and 1.7 for the spherical probe. No radar values are available for this altitude interval to serve as a comparison with the direct measurements. Millstone Hill radar results at midlatitudes for the winter of 1964 indicate an electron to ion temperature ratio of less than 1.6 for an altitude of 700 km with the ratio decreasing with increasing altitude.

Ion Composition

The high resolution magnetic ion mass spectrometer on Explorer XXXI could detect ions in the mass range of from 1 to 20 AMU whose number density was greater than 1/cc. The ion trap and spherical ion probe, through retarding potential techniques, served as low resolution spectrometers. These devices cannot distinguish closely spaced ions such as N^+ and O^+ but can identify widely separated ions whose abundance was on the order of 5 percent or more of the total ion concentration. For the comparison passes the results of the ion trap and spherical probe are separated into two groups—light ions lumped together as H^+ and heavy ions lumped together as O^+. This is reasonable since He^+ ions were a minor constituent on all passes, except WNK 550. The ionic composition results are given in Table IV, as percentages of total concentration. The magnetic ion mass spectrometer results are given for H^+, He^+, N^+ and O^+ ions.

The composition agreement obtained is quite good. On WNK 550 the insensitivity of the spherical probe to O^+ ions, as discussed in the section on plasma density, explains the composition disagreement with the other experiments.

These comparisons have indicated that the three experiments show good agreement on ion composition results. The only significant discrepancy could be due to instrument sensitivity limitations.

Discussion of Comparisons

The comparison results presented, although few in number and not sufficient for a statistical study, are felt to be typical of the results from the Explorer XXXI satellite. In the measurement of plasma density, electron temperature, and ion composition, there is no significant systematic disagreement between the various probes that cannot be recognized as arising from sensitivity or limiting considerations. There are, however, some random disagreements which require additional investigation. In general plasma density results were within ±20 percent of simultaneous Alouette II density measurements with occasional variations of up to about ±50 percent. Electron temperature results generally agreed to within ±10 percent with maximum variations of up to ±20 percent.

Of the probes employed, four used planar flush-mounted sensors (ion trap, electron trap, magnetic mass spectrometer, and Langmuir plate). The cylindrical electrostatic probes and the spherical ion probe were mounted on short booms about one foot from the satellite surface. This indi-

TABLE IV
ION COMPOSITION RESULTS

Station	Pass	Time	Magnetic Spectrometer				Ion Trap		Spherical Probe	
			H^+	He^+	N^+	O^+	H^+	O^+	H^+	O^+
Kano	368	0450	99	1	—	—	100	—	100	—
		0456	99	1	—	—	100	—	100	—
Orroral	546	0632	5	—	6	89	5	95	6	94
		0636	1	—	6	93	—	100	1	99
Winkfield	550	1412	78	12	2	8	84	16	100	—
		1417	86	7	1	6	96	4	100	—
Blossom Point	730	1841	6	1	7	86	7	93	3	97
		1844	23	3	5	69	28	72	29	71
		1848	35	3	3	59	36	64	43	57
Santiago	730	1902	1	—	2	97	—	100	2	98
		1904	1	—	3	96	—	100	2	98

cates that correct plasma diagnostics can be achieved for flush sensors operating within the satellite sheath. It is to be noted, however, that electron density values from the planar Langmuir plate (these results are not included in this paper) are always a factor of from 2 to 5 lower than the correct value. The planar electron trap appears to give reasonable results. The only significant difference in the two planar sensors is that the electron trap employs a swept surface area of about 55 cm^2 while the Langmuir plate swept surface area is about 12 cm^2. This suggests that satellite sheath penetration was not adequately achieved with the smaller area.

The general agreement in electron density measurements between the Alouette II sounder, cylindrical probe, and electron trap also indicates that large magnetic field orientation effects are not present. The anisotropy noted in electron temperature measurements could indicate a magnetic field influence.

The only area of major disagreement is in the measurement of ion temperature. The planar ion trap results are significantly greater than the results from the boom-mounted spherical probe. Although no serious conflict occurs in the relative trends observed, it is likely that in both cases there are measurement problems which preclude absolute significance for H^+ ion temperature results. A limited comparison of the measured ion temperatures with radar backscatter results has been been attempted. This indicates that the spherical probe results for O^+ may be somewhat low. No comparison data are available to resolve discrepancies in the measured H^+ temperatures. A possible source of error in the ion trap measurement is sheath curvature. The analysis assumes a planar sheath. Knudsen [6] has considered such perturbations to ion temperature measurements with planar traps and found the resultant error quite small. Additional effort is required to assess completely the ion temperature comparisons.

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Daytime Midlatitude Ion Composition Measurements

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An Argo D-4 (Javelin) rocket was launched from Wallops Island, Virginia, at 1828 GMT, Aug. 15, 1966, to rendezvous with a pass of the Explorer 31 and Alouette 2 satellites. The rocket reached an altitude of 720 km while the satellites were at 970 km. Identical magnetic mass spectrometers on the rocket and Explorer 31 satellite measured the composition of the ionosphere while the Alouette 2 topside sounder provided electron concentration profiles. Ten different ion species were observed. O^+ is the dominant constituent from 200 km to 1000 km with H^+ 5% and He^+ less than 1% of the O^+. The chemical equilibrium relation between H^+ and O^+ gives a value for the neutral hydrogen concentration of 6.2×10^4 at 250 km and a neutral gas temperature of 940°K. From the He^+ concentration at 400 km a rate coefficient for the He^+ loss reaction with N_2 of 1.2×10^{-9} cm^3 sec^{-1} is calculated. The NO^+ and O_2^+ scale heights from 200 to 300 km agree with those of N_2 and O_2 giving credence to the ion chemistry involved. In comparing the results from this rocket flight with those of other types of mass spectrometers flown in a similar time period, it is seen that the major discrepancy lies in the $n(H^+)$ measurements, the present result being lowest. The in-flight calibration tends to indicate that a mass spectrometer is more sensitive to light mass ions than to O^+. This phenomenon may account for the discrepancy noted.

INTRODUCTION

An Argo D-4 (Javelin) rocket, NASA 8.32 DA, was launched from Wallops Island, Virginia, at 1828 GMT on Aug. 15, 1966. It contained experiments to measure the electron concentration and temperature and the concentrations of the various species of positive ions in the ionosphere. The latter determinations were made by a sector-field magnetic mass spectrometer, the results of which are the subject of this paper. The payload, which was separated from the fourth (last)-stage motor at a differential velocity of ~1.5 meters/sec, reached an altitude of 723 km and was flown in conjunction with a pass of the Explorer 31 and Alouette 2 satellites. Figure 1 shows the trajectories of both the rocket and the satellites. At the point of crossing of the two paths the rocket was at its peak altitude of 723 km; the Explorer 31 satellite was at an altitude of 972 km. The time separation was 120 sec, the satellite arriving first as it proceeded south toward the equator. The Alouette 2 satellite was 23 min ahead of Explorer 31, but followed the same trajectory in local time. Data from the Alouette satellite are plotted at the same altitude as for the Explorer 31 satellite. It is assumed that any time fluctuations in the ionosphere are long compared with the time separation of the passage of the two satellites. This assumption appears reasonable from the smoothness and lack of structure in the ionosphere exhibited by the data.

EXPERIMENT

The mass spectrometer used to measure the ionospheric composition was a 1½-inch radius sector field magnetic instrument operated with a 2200 gauss permanent magnet and a swept ion accelerating voltage. Both the rocket and Explorer 31 satellite carried identical mass spectrometers, except that in the rocket the instrument was set to scan the mass range 1 to 32 amu with a 2-sec period, while in the satellite the mass range covered was 1 to 20 amu in a 3-sec period. Each instrument looked out the side of its respective vehicle through an aperture that contained no ion source since the mass spectrometers were designed to identify and measure the abundances of the positive ion species that exist in the ionosphere. The detector

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Fig. 1. Trajectories of Javelin rocket and Explorer 31 satellite showing direction of travel and local times. Satellite altitude at crossing of trajectories was 972 km; rocket was at peak altitude, 723 km.

systems consisted of a magnetic strip type electron multiplier followed by a logarithmic electrometer amplifier with a current sensitivity range of 2×10^{-12} amp to 1×10^{-6} amp. An internal calibration in the log amplifier supplied currents of 10^{-11}, 10^{-9}, and 10^{-7} amp to the amplifier once each 100 sec of operation. The resulting output voltages were used to generate constants in a calibration equation that relates the output voltage of the log amplifier to input current.

The general form of the data showing the peaks in the mass spectrum from the satellite mass spectrometer has been described elsewhere [*Hoffman*, 1967]. The data exhibit considerable roll modulation due to the high velocity of the satellite with respect to the mean ambient ion velocities. However, since the satellite attitude is known and the spacecraft is in a cartwheel orbit (spin axis normal to orbit plane), only the data taken in the ram position, when the angle of attack is a minimum and the sensitivity of the instrument to each ion species is a maximum, are used. The rocket data also exhibit a roll modulation, but since this vehicle was not nearly so well behaved as the satellite, its motion produced complicating effects. From a detailed determination of the rocket attitude, the angle of attack (the angle between the sensor aperture normal and the rocket velocity vector) at the time of measurement of each ion peak in each sweep of the mass spectrum was calculated, and an empirical correction to 0° angle of attack was made on each peak. Data points for angles of attack greater than 90° were omitted.

An ion mass spectrometer measures the relative abundances of the ions it samples from the ionosphere, but can be calibrated to yield absolute ion concentrations. There are several factors that cause it to discriminate against ions of heavy mass compared with those of light mass. First, the spectrometer scans the mass spectrum by varying the ion accelerating voltage that causes discrimination against the heavy mass ion. Second, light ions are more mobile and a larger light mass ion current is measured for equal ambient concentrations of

light and heavy mass ions. Third, the roll modulation, discussed above, is strongly mass dependent but causes a minimum of mass discrimination at 0° angle of attack. To correct for these discriminations the satellite mass spectrometer has been calibrated in-flight by detailed comparisons of the data to nearly simultaneous measurements of electron concentrations by the Alouette 2 topside sounder experiment [*Hoffman*, 1969]. Comparisons were made in regions of almost pure (>99%) H^+ of various concentrations up to $10^4/cm^3$ and a calibration curve for H^+ produced. By this calibration procedure the mass spectrometer was capable of determining absolute H^+ concentrations. A similar procedure was established for the O^+ data in the range from 10^2 to 5×10^5 ions/cm^3. Calibration for the other ion species (all minor constituents) was done by interpolating the H^+ and O^+ calibration curves. The over-all precision of the measurements after this calibration has been applied is of the order of 10%.

The rocket mass spectrometer data, after correction for roll modulation, have been normalized to the electron concentration measured at the F_2 maximum by the Alouette 2 sounder during its pass over the rocket trajectory 23 minutes earlier and to the Wallops Island ionosonde data (L. Lohr, personal communication, 1967). Then, the sensitivity of the spectrometer to each ion species was calibrated by comparing its amplitude to the corresponding ion peak in the Explorer 31 mass spectrometer spectrum which, in turn, had been calibrated as described above. Since the rocket and satellite velocities are quite different, and the collection efficiencies of ions may be a function of vehicle velocity, there may be some uncertainty introduced in the rocket data by the calibration technique used. However, since both instruments were measuring essentially the same ionosphere, the results should agree, and this was basically the assumption used in forcing the uncalibrated rocket data to be consistent with the calibrated satellite data. The rocket data precision in measuring absolute ion concentrations is estimated to be of the order of 30%.

There may be some question regarding the satellite calibration technique when H^+ is a minor ion, the case in hand, since the size and

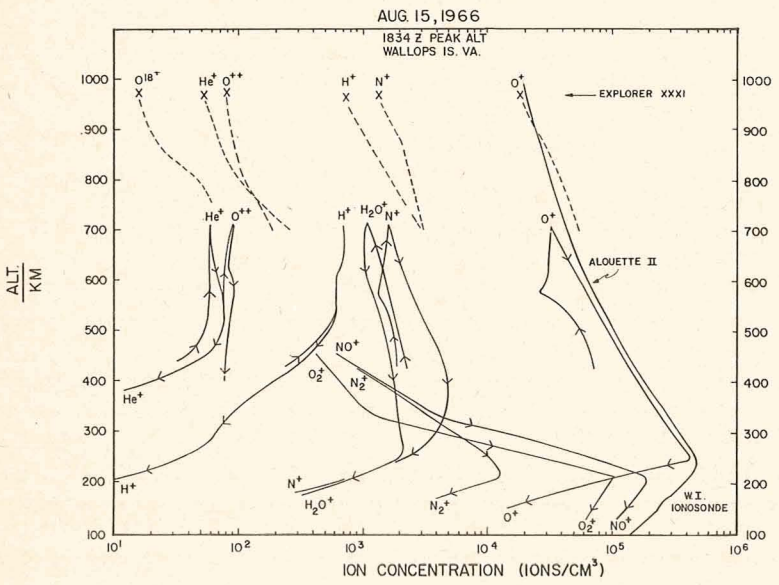

Fig. 2. Ion concentration as a function of altitude showing both the rocket data (solid lines) and the satellite data (broken lines). *X*'s refer to the satellite data at the point of intersection of the two trajectories. The Alouette 2 curve is the electron concentration from the topside sounder experiment matched to the Wallops Island ionosonde data at the *F* maximum.

TABLE 1. Latitude Gradient (% Change per Degree) in Ion Concentration at 700 km from Rocket and Satellite Data Average gradient between 37.5°N and 18.7°N.

Ion Mass	Latitude Gradient at 700 km
1	18
4	17
8	5.3
14	4.5
16	2.5

shape of the ion collection volume in front of the instrument aperture may depend on the mass of the dominant ion species. This effect could cause an error in both the satellite and rocket H^+ measurements. However, this effect probably does not account for more than an additional 20% error to the H^+ determinations as is evidenced by the agreement of results from several of the ionospheric detectors on the Explorer 31 satellite [*Donley et al.*, 1969]. Also the smoothness of the transition from O^+ and H^+ and the agreement with the Alouette 2 data shown in Figure 5 of *Hoffman* [1969] would indicate a rather small error from this phenomenon.

Results

Data were obtained on the rocket flight from 425 km on the upleg to the peak of flight, 723 km, and down to 130 km on the descent. Figure 2 shows a plot of the concentrations of each ion species as a function of rocket altitude with the direction of the arrows indicating up- or downleg of the flight. The data plotted here have been corrected as described in the previous section. The solid curve to the right in the figure shows the electron concentration measured by the Alouette 2 topside sounder (G. L. Nelms, personal communication, 1968) matched to the Wallops Island ionosonde (L. Lohr, personal communication, 1967) data taken at the time of flight of the rocket.

The Explorer 31 ion composition results plotted as a function of height are shown at the top of the figure as dashed lines. The X's are the values at the intersection of the rocket and satellite trajectories (Figure 1). It should be noted that by extending all of the rocket ion profiles up to the satellite altitude there would be reasonable agreement between the rocket and satellite data except for the mass 18 ion. In the rocket data, mass 18 is due to water vapor that has outgassed from the instrument package, and has charge exchanged with ambient O^+, while the satellite mass 18, being 2 orders of magnitude lower, is O^{18+}, the water vapor having long since been outgassed from the satellite. Further evidence that the rocket mass 18 peak is H_2O^+, and is outgassing from the rocket payload, is seen from the fact that the upleg data lies above the downleg data. For both O^+ and N^+ the opposite is true, i.e., the downleg concentrations are greater.

The O^+ profile follows the Alouette 2 $N(h)$ profile reasonably well. O^+ is by far the dominant constituent, being 94.2% (including 2.8% H_2O^+) of the total ion concentration at 700 km. N^+ is next at 4.1%, and H^+ at 1.7%. H^+ being a very minor constituent, even at the satellite altitude, indicates that its crossover with O^+ lies well above 1000 km. A mass 8 ion is observed throughout the rocket data and is identified as O^{++}. Its scale height is very large (actually it is negative but could be infinite within the experimental error) indicating a doubly charge constituent of half the mean ion mass [*Mange*, 1960] (P. W. Mange, personal communication, 1969). It is unlikely that the mass 8 is He_2^+, since its concentration is greater than that of He^+. The very low He^+ concentration shown here, 0.15%, is typical of the He^+ values observed by the Explorer 31 satellite in midlatitude regions.

The molecular ion constituents, NO^+, O_2^+, and N_2^+ all have maximum concentration below the F_2 maximum. There is a significant change of slope in the NO^+ and O_2^+ at about 350 km, but not in the N_2^+ data. The data points below 200 km are subject to greater uncertainties than those at higher altitudes due to the increased rocket velocity and correspondingly greater roll modulation of the ion peak amplitudes. The rocket is also tumbling and, therefore, yields relatively few points when the angle of attack is sufficiently small to enable a roll modulation correction to be made. The result is that the altitude of the maxima of the molecular constituents may be in error by up to 30 km.

The bottoms of the dashed curves are the Explorer 31 ion concentrations at 700 km at

18.7°N latitude. Since the rocket peak values are at 37.5°N latitude, the difference between these sets of values shows a latitude gradient in ion concentration at constant altitude (700 km). The values of the gradient are given as a function of ion mass in Table 1. It can be seen that the smallest ion mass exhibits the largest gradient. All of the ion concentrations increase toward the equator, but the lighter ions increase faster.

Figure 3 shows the Explorer 31 ion concentration data as a function of both latitude and altitude. The vertical Alouette 2 $N(h)$ profile as well as the electron concentration along the Alouette 2 trajectory are also shown in the figure. Ten different ion species are observed. The more abundant species are also shown in Figure 2. Of the minor constituents N^{++}, mass 7, reasonably follows N^+ as does O^{++}, mass 8, and O^+. The N^{++}/N^+ ratio varies from 6 to 7 $\times$ 10^{-4}, whereas the O^{++}/O^+ ratio is 3 $\times$ 10^{-3}.

N^{15+} is observed as is O^{18+}. The N^{15+}/N^{14+} ratio varies from 2.8 $\times$ 10^{-3} at 700 km to 2.1 $\times$ 10^{-3} at 1100 km, whereas the O^{18+}/O^{16+} ratio is 1.6 $\times$ 10^{-3} and 0.57 $\times$ 10^{-3} at the same altitudes, respectively. These values for normal ground level neutral nitrogen and oxygen are 3.66 $\times$ 10^{-3} and 2.04 $\times$ 10^{-3}, respectively. It would be reasonable to expect a diffusive separation of these isotopes at the satellite altitudes, and this is qualitatively borne out by the data.

The mass 2 ion is identified as deuterium. It has a ratio to H^+ of 1.1 $\times$ 10^{-3}. The ground level D/H ratio is 1.5 $\times$ 10^{-4}. Both D^+ and H^+ are formed by the well-known chemical equilibrium reaction with oxygen [*Hanson and Ortenburger*, 1961]

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

written here for deuterium. If the rate constant for deuterium is greater than for hydrogen, then one would expect a greater D^+/H^+ ratio even at 700 km than for their neutral counterparts at ground level. It has been observed by the Explorer 31 mass spectrometer that the D/H ionic ratio is generally of the order of 10^{-3} below 1000 km, but approaches the ground level D/H value above 2000 km.

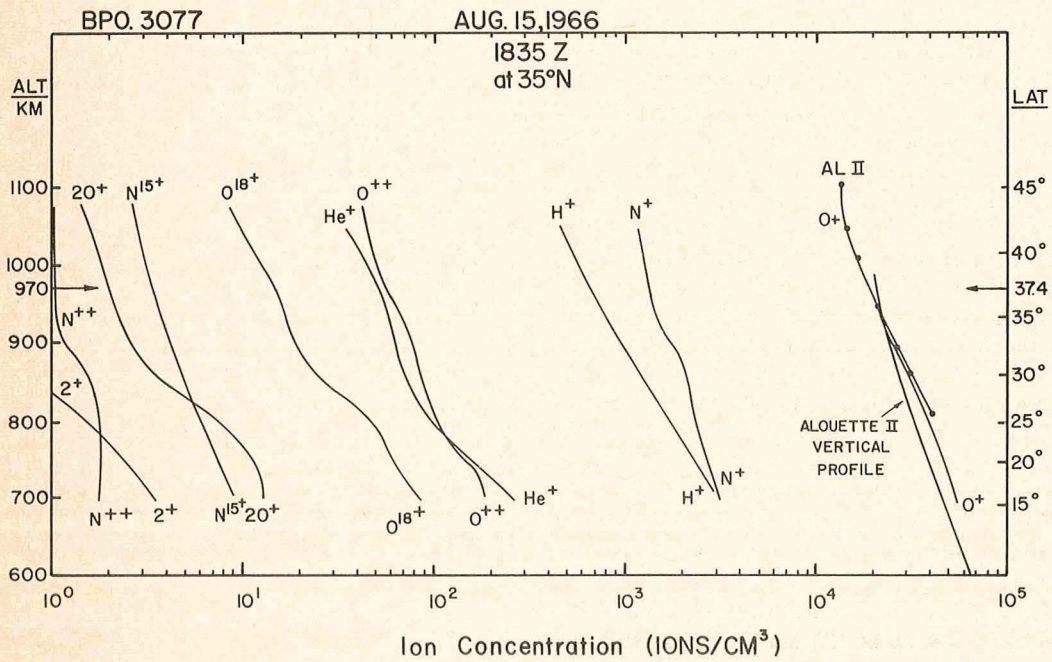

Fig. 3. Ion concentration from the Explorer 31 satellite mass spectrometer as a function of both altitude and latitude. The arrow at 970 km shows the point of intersection of the rocket and satellite trajectories. The dots on the O^+ curve give the electron concentrations along the Alouette 2 satellite trajectory. The Alouette 2 vertical profile is at 37°N.

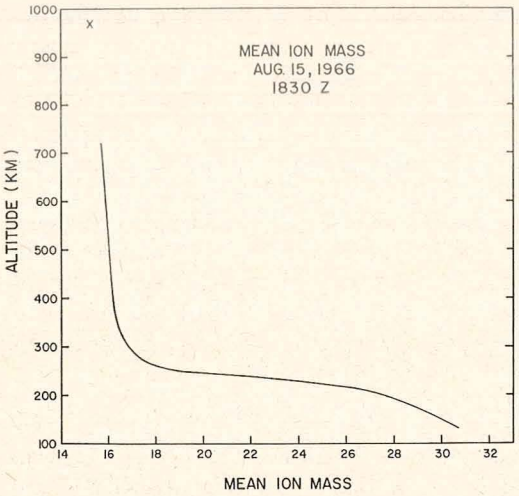

Fig. 4. Mean ion mass as a function of altitude.

The mass 20 ion is identified at Ne^+. The ratio of Ne^+/He^+ is 0.045 and is fairly constant with altitude, a fact which is difficult to explain due to the large mass difference between these gases. The ground-level ratio of neon to helium is 3.5. Therefore, the 200 times decrease in the ionic ratio over the ground level neutral value could be attributed to a gravitational separation due to the large mass ratio. Since both are noble gases they are probably formed by direct photoionization of neon and helium. The photoionization rate coefficient for helium is 1×10^{-7} sec^{-1}; for neon, it is 3×10^{-7} sec^{-1} [*Hinton and Taeusch*, 1964]. The loss mechanism for Ne^+ is not known, but it could be assumed to be by charge exchange with N_2 in a similar manner to helium. For the He^+/Ne^+ ratio to remain constant throughout the chemical equilibrium region, as is observed, a flow mechanism may have to be invoked.

The mean ion mass derived from the rocket profiles is plotted against altitude in Figure 4. The value at the satellite altitude is given by the X. Since O^+ is the dominant constituent even at 1000 km, the mean ion mass is approximately 16 from there down to nearly 250 km where the molecular constituents become important. Finally at 130 km the mean ion mass, 30.7, consists mainly of a combination of NO^+ and O_2^+.

The ion and electron temperatures were measured by other instruments on the Explorer 31 satellite simultaneously with the ion composition data. At the time the satellite crossed the rocket trajectory the ion temperature was measured by the spherical ion trap to be 2100°K (G. L. Wrenn, personal communication, 1968), whereas the electron temperature was determined by a planar electron trap to be approximately 3700°K (J. L. Donley, personal communication, 1968), and by the cylindrical electrostatic probe to be 3650°K (L. Brace, personal communication, 1969). During the preceding orbit, two hours earlier, Brace found Te to be 3250°K.

Discussion

O^+ has been found to be the dominant constituent of the ionosphere at all altitudes observed above the F_2 maximum with H^+ always a very minor constituent (4% of the O^+ at 970 km). In the lower region of the ionosphere H^+ and O^+ are in chemical equilibrium through the well known charge-exchange reaction [*Hanson and Ortenburger*, 1961],

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

A plot of the ionic ratio as a function of reduced altitudes [*Hanson*, 1962, indicated by km′] is given in Figure 5. The ratio points lie on a reasonably straight line up to an altitude of 450 km indicating the region of chemical equilibrium. Since equation 2 represents both

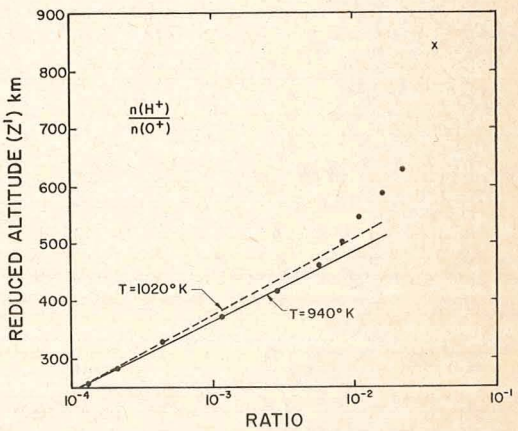

Fig. 5. $n(H^+)/n(O^+)$ as a function of reduced altitude. Data are shown as dots. The solid curves give scale height neutral gas temperatures in the chemical equilibrium region.

the source and sink for H^+, the scale height of the ratio of $n(H^+)$ to $n(O^+)$ is characterized by an effective mass of 15 amu and is a function of the neutral gas temperature. From the observed scale height of 53 km′, the temperature of the neutral gas is 940°K. It is assumed that $T_g = T_i$ here.

From a model of the neutral atomic oxygen distribution and with the aid of equation 2, the neutral hydrogen distribution can be calculated for the region of chemical equilibrium. The model atmosphere of *Harris and Priester* [1962] at a temperature of 962° and 10.7-cm flux of 100×10^{-22} W/m² cps was used for the atomic oxygen profile that is shown in Figure 6. The measured oxygen values of *Krankowsky et al.* [1968] for a summer daytime rocket flight at White Sands are given as dots in the figure to which the Harris and Priester model $n(O)$ was normalized at 200 km, the normalization constant being 0.77. These oxygen measurements made on June 21, 1967, over White Sands, New Mexico, at 1249 MST are assumed to be applicable to the August 15, 1966, time of the Javelin rocket flight at Wallops Island for the following reasons: (*a*) the *Kp* indices for August 15 and June 21 are 10 and 9⁻, respectively (both are termed quiet days), and (*b*) the ion composition, as measured by the Explorer 31 satellite mass spectrometer at the same location and within 30 minutes of the same local time on both days, is essentially identical. O^+ is the dominant constituent at 1000 km at a concentration of 1.7×10^4 on August 15 and 1.6×10^4 on June 21. The H^+/O^+ ratio is 0.039 on August 15 and 0.035 on June 21 with N^+ being the second most abundant constituent on both days at 7.5% of O^+.

The calculated atomic hydrogen distribution from equation 2 and the $n(O)$ curve is then given as the dashed curve in Figure 6. For comparison, the Harris and Priester model hydrogen profile is given as the solid $n(H)$ curve normalized to the calculated $n(H)$ at 250 km′. The normalization factor here is 4.6. The calculated values agree well with the model up to 450 km′ where the significant departure indicates that the H^+ is no longer in chemical equilibrium with O^+.

Krankowsky et al. quote a probable accuracy of 25% for the atomic oxygen number density; the $n(H^+)/n(O^+)$ ratio probable accuracy is 20%. Therefore, the $n(H)$ probable accuracy is 45%.

The measured altitude profile for $n(He^+)$ is plotted against reduced altitude (shown as dots) in the right side of Figure 7. He^+ is pro-

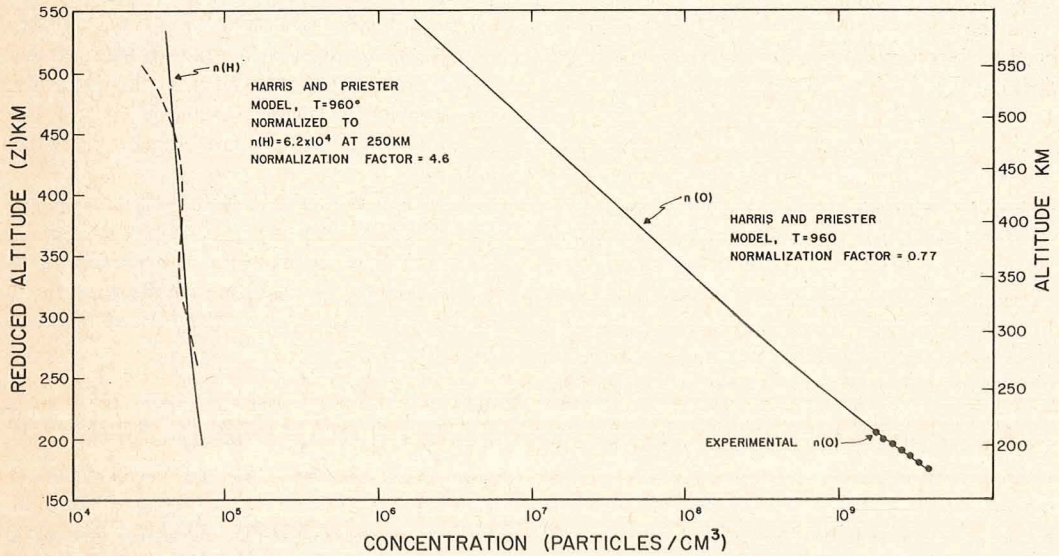

Fig. 6. Concentrations of O and H as a function of reduced altitude. The model $n(O)$ is normalized to a rocket measurement (see text) at 200 km. Calculated $n(H)$ is the dashed curved. Model $n(H)$ is normalized to calculated value at 250 km′. Normalization factor is 4.6.

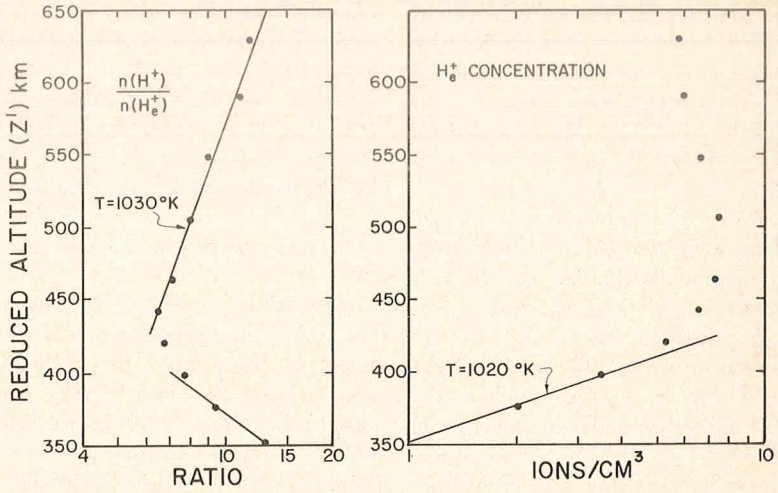

Fig. 7. $n(He^+)$ and $n(H^+)/n(He^+)$ as a function of reduced altitude. Lower part of $n(He^+)$ curve shows He^+ in chemical equilibrium. Scale height temperature is 1020°K. Ratio curve gives apparently false impression of diffusive equilibrium in upper portion of curve.

duced in the atmosphere by the photoionization of neutral helium and lost by charge-transfer reactions with N_2 (principally) and O_2 [*Bauer*, 1966]. In the chemical equilibrium region, indicated by the solid line in Figure 7, the altitude distribution of $n(He^+)$ is governed by a scale height with an effective mass of 24 amu. From the measured scale height, 36 km′, up to 400 km′, the neutral gas temperature, T_g, is 1020°K, in reasonable agreement with the T_g from the $n(H^+)/n(O^+)$ curve. The 1020°K curve is also shown in Figure 6. The chemical equilibrium distribution of $n(He^+)$ is given by

$$n(He^+) = \frac{I_{He} n(He)}{k n(N_2)} \qquad (3)$$

where I_{He}, the photoionization rate coefficient for He, is 1×10^{-7} sec $^{-1}$ [*Hinton and Taeusch*, 1964], and k is the rate coefficient for the loss process with N_2 given by *Ferguson et al.* [1964] to be 1.3×10^{-9} cm^3 sec^{-1}. From the Harris and Priester model atmosphere used previously for $n(O)$, the values of $n(He)$ and $n(N_2)$ were found at 370 km′, again having normalized the model curves to the data of Krankowsky et al. at 200 km. In this case the normalization factors were 0.7 for He and 1.2 for N_2. From the measured $n(He^+)$ at 375 km′, 20 ions/cm^3, k is found to be 1.2×10^{-9} cm^3 sec^{-1} in good agreement with *Ferguson et al.* [1964].

Above 400 km′ $n(He^+)$ deviates from the scale height associated with chemical equilibrium and enters a region involving gradients of the ion and electron temperature, T_i and T_e, and vertical transport of ions.

The ratio of $n(H^+)/n(He^+)$ in the chemical equilibrium region is characterized by a scale height with an effective mass of -17 amu. The measured scale height from the left side of Figure 7 gives a temperature of 1600°. However, a 20% error in $n(He^+)$ at 350 km′ implies a temperature range from 800° to 2000°K due to the very narrow altitude range in which the ionic ratio is in chemical equilibrium and the correspondingly large change in slope this error produces.

Above 450 km′, the $n(H^+)/n(He^+)$ ratio appears to be in diffusive equilibrium. It can be shown that the ratio of the concentrations of two ion species in diffusive equilibrium as a function of altitude depends only on the ion temperature, T_i

$$\frac{n(X_1^+)}{n(X_2^+)} \alpha \exp\left[\int_{z_0'}^{z'} \frac{(m_2 - m_1)}{k T_i} g_0 d_z\right] \qquad (4)$$

where g_0 is the gravitational acceleration at ground level and z' is the reduced altitude. Applying equation 4 to H^+ and He^+, the scale height above 450 km′ of $n(H^+)/n(He^+)$ should have an effective mass of 3 amu and indeed the measure slope of the curve in Figure 7 (left

side) gives $T_i = 1030°K$, constant from 450 km′ to 650 km′. However, G. L. Wrenn (personal communication, 1968) obtains a value for T_i at the Explorer 31 altitude (870 km′) from the spherical ion trap experiment of 2100°K. If it is assumed that $T_i = T_e$ at 400 km′, the upper boundary of the chemical equilibrium region, and $T_e = 940°K$ from the $n(H^+)/n(O^+)$ data, a gradient in T_i of 2°/km is required to reconcile the two results. Clearly the slope of $n(H^+)/n(He^+)$ does not show this gradient. A possible conclusion to be drawn is that these ion species are not in diffusive equilibrium, but vertical transport of ions distorts the apparent diffusive equilibrium conditions, and equation 4 does not apply to give a meaningful scale height temperature.

In the region from 220 km to 300 km the molecular ion species NO^+ and O_2^+ have scale heights of 30 km and 26.5 km, respectively. If the formation processes of these ions are governed by charge-exchange reactions with N_2 and O_2 respectively, and the ionic destruction is by dissociative recombination, then they should be distributed according to the scale heights of their neutral counterparts in the region above 200 km where chemical equilibrium occurs [*Holmes et al.*, 1965]. The Harris and Priester Model Atmosphere used previously gives scale heights of 29 km and 26 km for N_2 and O_2. The agreement with the ionic scale heights lends credence to the ion chemistry involved and the neutral gas temperature of 940°K.

The increase in slope of NO^+ and O_2^+ at 330 km is not explained, but is believed to be outside the limits of experimental error. Perhaps, an additional source of these ions is indicated here. Also, diffusion would be expected to dominate charge exchange above some such altitude. In diffusive equilibrium the scale heights of these molecular ion species would be somewhat greater than that of their neutral counterparts (the mean ion mass in 16) [*Mange*, 1960], which tends to agree with the observations in direction, but not so well in magnitude.

The scale height of N_2^+ being more than twice that of N_2 would tend to indicate that the major source of N_2^+ is not direct photoionization of N_2. Perhaps the He^+ loss reaction with N_2 is important. The agreement between the N_2^+ and NO^+ gradients above 330 km may suggest a common source operating in this region.

Several other direct measurements of the ionosphere over Wallops Island were made in the same year as this flight utilizing different types of mass spectrometers. *Brinton et al.* [1968] flew a Bennett RF instrument on March 2, 1966, and *Maier* [1969] used a Wien velocity filter on a flight on October 6, 1966. Both were early afternoon shots. There is general agreement as to the gross features of the ionosphere; O^+ is the dominant constituent, and He^+ is a very minor ion. There is, however, what appears to be a significant difference in the concentrations of H^+, although the shapes of the profiles are similar, at least in the upper regions. The mass spectrometer in the current study, when calibrated in-flight as described above, yields nearly an order of magnitude lower $n(H^+)$ values than are given by the other two instruments. However, the $n(H^+)/n(O^+)$ ratio curve yields a reasonable value for $n(H)$. The calibration data show that the ion current measured by a mass spectrometer for light ions (more so for H^+ than for He^+) is greatly enhanced over that for heavy ions (O^+) by a combination of the higher mobility of the light ions, the draw-in fields of the mass spectrometer entrance aperture, and the vehicle potential. The result is that an in-flight calibration is essential to producing meaningful ionic ratio and concentration measurements.

Conclusion

Data obtained by a sector-field magnetic mass spectrometer from a Javelin (Argo D-4) rocket flight from Wallops Island, Virginia, flown to rendezvous with a pass of the Explorer 31 satellite carrying an identical mass spectrometer, show O^+ to be the dominant constituent of the ionosphere at all altitudes observed above 200 km. H^+ is of the order of 5%, and He^+ is less than 1%. The chemical equilibrium relation between H^+ and O^+ gives a value for the neutral hydrogen concentration of 6.2×10^4 at 250 km and a neutral gas temperature of 940°K. From the He^+ concentration at 375 km′, a rate coefficient for the He^+ loss reaction with N_2 of 1.2×10^{-9} cm^3 sec^{-1} is calculated. A gradient in T_i of 2°/km from 450 to 970 km is inferred from the rocket data and the measured T_i at the Explorer 31 altitude. The NO^+ and O_2^+

scale heights agree well with the N_2 and O_2 scale heights, giving credence to the ion chemistry involved. In comparing the present results with those of other mass spectrometer flights in a similar time period, it is seen that there is a difference in the $N(H^+)$ measurements, the present result being lowest. The in-flight calibration tends to indicate that a mass spectrometer is overly sensitive to light mass ions compared with O^+.

Acknowledgments. The authors gratefully acknowledge the help of L. Kegley, J. Kruly, W. Wassam, and P. Stevanus in the design and construction of the rocket payload. The NRL Engineering Services Division constructed the mechanical hardware. Fruitful discussions were held with Dr. P. Mange.

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MEASUREMENTS OF THE MASS 8 ION IN THE TOPSIDE IONOSPHERE

Transactions, American Geophysical Union, 50, 259, 1969

Presented at 50th Annual Meeting of American Geophysical Union, Washington, D. C., April 1969.

Measurements of the Mass 8 Ion in the Topside Ionosphere. An ion with a mass to change ratio of 8 amu is observed in the data obtained by identical mass spectrometers on the Explorer XXXI satellite and on an Argo D4 (Javelin) rocket flown from Wallops Island, Va. on Aug. 15, 1966. At mid latitudes in the northern hemisphere, the $8^+/O^+$ ratio has been found to be of the order of 3×10^{-3} at approximately 1000 km. Also, the $8^+/He^+$ ratio is of the order unity. From the rocket data, the altitude profile of the 8^+ ion between 500 and 700 km gives a scale height of the order of 900 km. The mean ion mass at this time was approximately 16 amu. An ion of M=16, Z=2 in diffusive equilibrium in an ionosphere of mean ion mass = 16 amu would have a very large scale height. Therefore, the 8^+ ion is identified as O^{++} rather than He_2^+ at low altitudes (below 1500 km). The 8^+ ion is also observed as high as 3000 km in regions where no O^+ ions are detected. The $8^+/He^+$ ratio lies in the range from 10^{-3} to 10^{-1}, while the concentration of 8^+ ions varies from 5 to $0.5/cm^3$, and tends to go inversely with the He^+ concentration. The mean ion mass is nearly 1 in these regions, so O^+ and O^{++} would have essentially the same scale heights. From these data, the possibility of the 8^+ ion being He_2^+ at high altitudes is not ruled out.

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Mass Spectrometer Measurements of Ionospheric Composition

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Magnetic deflection mass spectrometers have been used by the author since 1964 to study the composition of the ionosphere from rockets and satellites. Such instruments have been successfully flown on four high altitude rockets and one satellite, the Explorer XXXI, which operated for 2-1/3 years in orbit. Basically, the instrument consisted of a 1-1/2" radius 60° sector-field magnetic analyzer (permanent 2200 gauss magnet) with an electron multiplier detector followed by a 6 decade logarithmic electrometer amplifier. The mass spectra from 1 to 20 or 32 amu (satellite or rocket instrument, respectively) are produced serially by the repetitive high voltage sweep circuit, the position of each peak in the spectrum identifying the ion species, and the amplitude of the peak being proportional to the logarithm of the concentration of ions in the vicinity of the entrance aperture of the mass spectrometer (mounted normal to the spin axis), which is dependent on the satellite attitude, velocity, and potential and has a complex relation to the ambient ion concentration. An in-flight calibration is necessary to obtain absolute ion concentrations.

The in-flight calibration was done for the Explorer XXXI mass spectrometer by comparing the total ion current (the sum of all the peaks) under various conditions of ion concentrations with nearly simultaneously acquired electron density data from the Alouette II topside sounder satellite (Hoffman).[1] The overall precision of the measurements, after applying this calibration procedure, is of the order of 10% as is demonstrated by comparisons with other Alouette II data and the other direct measurements probes on the Explorer XXXI satellite (Donley et al).[2]

Since data from a spin stabilized cartwheel orbit type of satellite like Explorer XXXI are highly roll modulated (Hoffman),[3] and only the ram position data are used, the spatial resolution of the data is of the order of 100 to 200 km for spin periods of 2 to 3 rpm. On an oriented satellite such that the angle of attack is maintained near 0° the spatial resolution would be the mass spectrum sweep period times the vehicle velocity, or from 6 to 20 km.

A magnetic deflection mass spectrometer exhibits good mass resolution and sensitivity as is evidenced by the Explorer XXXI data. Ten different ion species have been observed between mass 1 to 20 amu at $1(H^+)$, $2(D^+)$, $4(He^+)$, $7(N^{++})$, $8(O^{++}$ or $^2He^+)$, $14(N^+)$, $15(^{15}N^+)$, $16(O^+)$, $18(H_2O^+$ or $^{18}O^+)$ and $20(Ne^+)$ amu, (Hoffman).[3] The sensitivity of the Explorer XXXI mass spectrometer to H^+ ions is of the order of $0.3/cm^3$ and to O^+ ions of the order of $10/cm^3$.

A summary of recent scientific advances obtained with the magnetic deflection mass spectrometer follows. In general it has been found from the Explorer XXXI data that below 1000 km O^+ is the dominant ion species in the ionosphere (see Fig. 1). N^+ varies from 5 to 30% of the O^+ and H^+ is generally a minor constituent, occasionally, as low as 5% of the O^+. Above about 2000 km at mid to low latitudes the ionosphere generally consists of the order of 99% H^+, the remainder being He^+, D^+, and 8^+. The cross-over altitude between O^+ and H^+ is quite variable, and is a function of several parameters. He^+ is a very minor constituent at all altitudes being of the order of a few % to less than 1%.

An ion peak at mass 8 amu is frequently observed in the data, always at low altitudes and not infrequently above 2000 km. In regions where O^+ is the dominant constituent, the mass 8 ion is identified as O^{++}, formed by photoionization of O^+. Its relative abundance is of the order of a few x 10^{-3} of the O^+. Likewise a peak

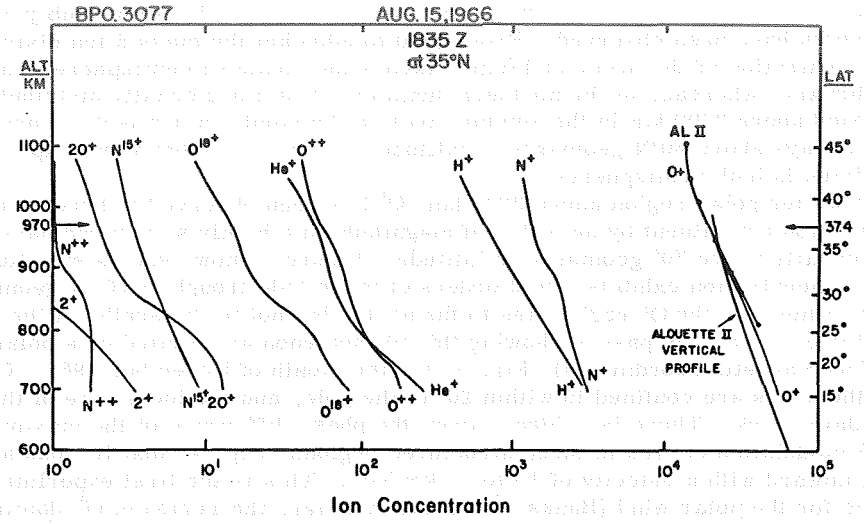

Fig. 1. Typical low altitude data showing ion concentration versus altitude and latitude. Ten different ion species are observed. Alouette II electron concentrations are also given.

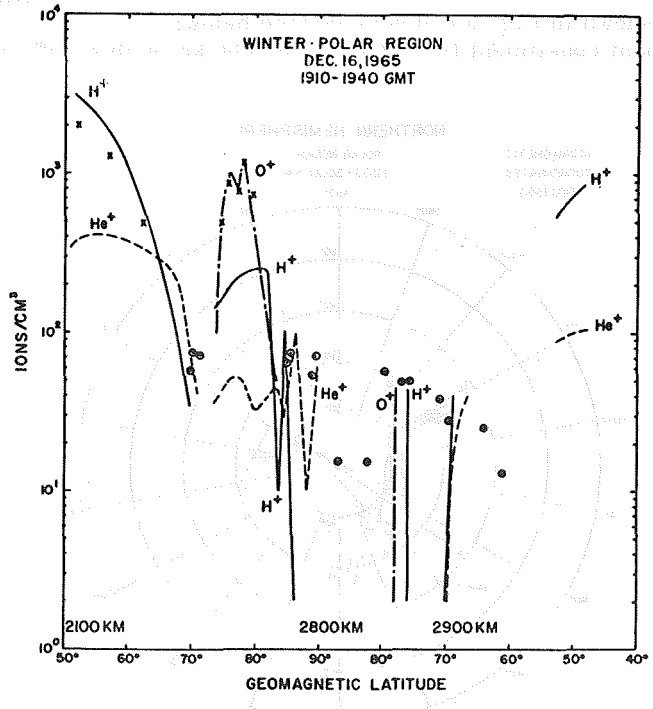

Fig. 2. Ion concentrations versus geomagnetic latitude for northern polar region. x's are Alouette II data reduced by standard method. ⊙'s are Alouette II data by Hagg method. In region around 80-85° N, H^+ ions have an upward drift velocity of 10 to 15 km/sec. N^+ is also observed at concentration of 6% of O^+, (not shown in figure).

at mass 7 is identified as N^{++}. These are the first data in which the doubly charged constituents have been observed. From 2200 to 3000 km the mass 8 ion distribution, at a concentration of the order of $1/cm^3$, favors the southern hemisphere in January and February, whereas, in the northern summer, it is more equally distributed. O^+ is found above 2200 km in the summer only in the northern hemisphere and, then, almost always above 60°N geomagnetic latitude. On the other hand, He^+ appears at all times in both hemispheres.

In the winter polar region above 2200 km, O^+ has been observed to become the dominant ion constituent by an order of magnitude in a highly structured narrow region usually above 70° geomagnetic latitude. Figure 2 shows such a situation. The H^+ concentration exhibits 1 to 2 orders of magnitude trough at 70° N geomagnetic latitude, whereas, the O^+ region lies to the north, but not to the south, of the trough. Trajectories of various passes showing this phenomenon are plotted on a polar graph (geomagnetic coordinates), Fig. 3, for the month of December 1965. Generally, the areas are confined to within 20° of the pole, and the local time of the orbits is dawn-dusk. There is evidence from the phase difference of the maxima in the roll modulation curves in these structured regions, Fig. 4, that H^+ ions are flowing upward with a velocity of 10 to 15 km/sec. This is the first experimental evidence for the polar wind (Banks).[4] In the summer, the region of O^+ dominance and the flow of H^+ ions is considerably broader, extending down to 55° or 60° N and shows much less structure than in winter.

A Javelin rocket, flown on August 15, 1966 to rendezvous with a pass of the Explorer XXXI satellite, carried a mass spectrometer, identical to that in the satellite, which was calibrated in-flight against the satellite instrument (Hoffman et al.[5]). The results are shown in Fig. 5 and summarized below:

O^+ is the dominant constituent from 200 km to 1000 km with H^+ 5% and He^+ less

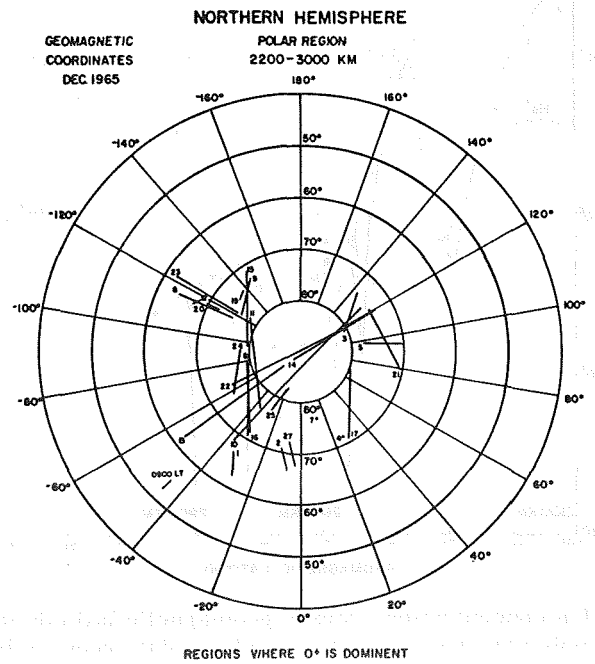

Fig. 3. Northern polar region (geomagnetic coordinates) showing satellite trajectories of regions where O^+ is the dominant constituent above 2200 km and H^+ ions are streaming outward.

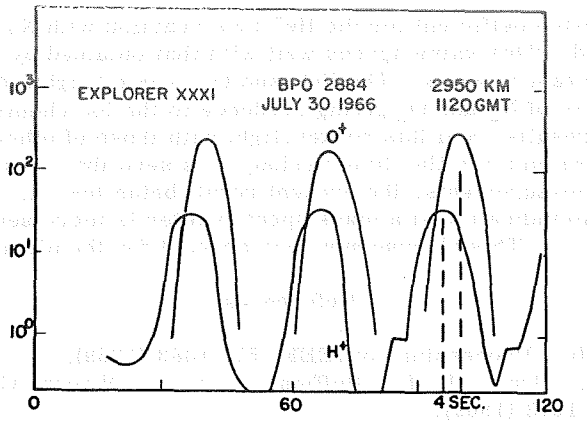

Fig. 4. Ion concentration versus time showing phase difference in the roll modulation maxima of H^+ and O^+.

than 1% of the O^+. The chemical equilibrium relation between H^+ and O^+ gives a value for the neutral hydrogen concentration of 6.2×10^4 at 250 km and a neutral gas temperature of 940°K, using a Harris and Priester model atmosphere[6] normalized to Krankowsky et al.[7] value of n(O) at 200 km. From the He^+ concentra-

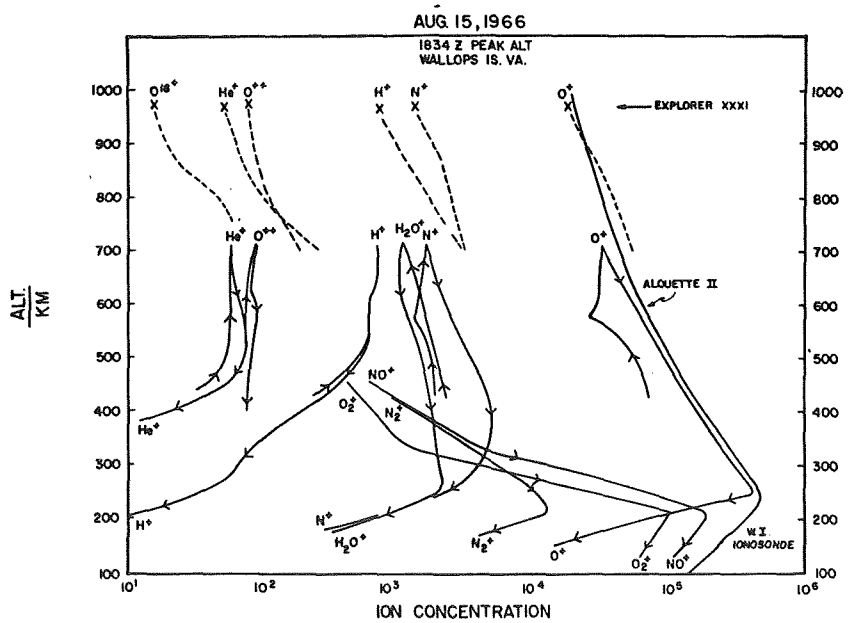

Fig. 5. Ion concentration as a function of altitude showing both the rocket data (solid lines) and the satellite data (broken lines). x's refer to the satellite data at the point of intersection of the two trajectories. The Alouette II electron density from the topside sounder experiment is matched to the Wallops Island ionosonde data at the F maximum.

tion at 400 km a rate coefficient for the He^+ loss reaction with N_2 of $1.2 \times 10^{-9} cm^3 sec^{-1}$ is calculated. This value agrees well with that obtained by Ferguson et al.[8] from laboratory measurements. The NO^+ and O_2^+ scale heights from 200 to 300 km agree with those of N_2 and O_2 giving credence to the ion chemistry involved. In comparing the results from this rocket flight with those of other types of mass spectrometers flown in a similar time period, it is seen that the major discrepancy lies in the $n(H^+)$ measurements, the present result being lowest. The in-flight calibration tends to indicate that a mass spectrometer is more sensitive to light mass ions than to O^+. This phenomenon may account for the discrepancy noted.

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Studies of the Composition of the Ionosphere with a Magnetic Deflection Mass Spectrometer

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University of Texas at Dallas

A magnetic sector field mass spectrometer on the Explorer XXXI satellite, when calibrated in flight against electron concentration data from the Alouette II topside sounder satellite, measures the absolute concentrations of the various positive ion species in the ionosphere. Data at 500 km show as many as ten different ion species in the ionosphere with 0^+ as the dominant species. Above 2000 km over the polar regions, 0^+ is again the dominant species and H^+ ions have been observed to be streaming upward at 10 to 15 km/s.

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Studies of the Composition of the Ionosphere with a Magnetic Deflection Mass Spectrometer

JOHN H. HOFFMAN

Measurements of the composition of the ionosphere using rockets and satellites have been made with magnetic deflection mass spectrometers since 1964. Such instruments have been successfully flown on four high altitude rockets and one satellite, the Explorer XXXI, which operated for $2\frac{1}{3}$ years in orbit. Basically, the instrument consisted of a $1\frac{1}{2}$-in. radius 60-deg sector-field magnetic analyzer (permanent 2200 gauss magnet) with an electron multiplier detector followed by a six decade logarithmic electromer amplifier. An entrance aperture, covered by a fine wire screen at -6 v with respect to the vehicle skin potential and mounted normal to the vehicle spin axis, draws ions from the atmosphere into the instrument, where a negative sweep voltage (-4000 to -200 or -150) produces a mass scan to 1 to 20 amu (satellite) or 1 to 32 amu (rocket) with a period of 2 or 3 sec. An internal calibrator in the log amplifier supplies currents of 10^{-11}, 10^{-9}, and 10^{-7} amp to the amplifier input periodically, enabling the amplifier output voltage to be related to input current.

The mass spectra are produced serially by the repetitive high voltage sweep circuit, as is shown in Fig.1, the position of each peak in the spectrum identifying the ion species, and the amplitude of the peak being proportional to the logarithm of the concentration of ions in the vicinity of the entrance aperture of the mass spectrometer, which is dependent on the satellite attitude, velocity, and potential, and has a complex relation to the ambient ion concentration. An in-flight calibration, described in the following, is necessary to obtain absolute ion concentrations.

The data from the satellite experiment shows considerable roll modulation (Fig.1) due to the high vehicle velocity (especially the satellite) with respect to the mean ambient ion velocities and the side mounted (normal to the spin axis) entrance aperture of the mass spectrometer. However, since the satellite attitude is known and the spacecraft is in a cartwheel orbit (spin axis normal to orbit plane), it is most practical to use only the data taken in the ram position, when the angle of attack is a minimum, and the sensitivity of the instrument to each ion species is a maximum. The rocket data are also roll modulated, and an empirical correction is made on each ion peak amplitude to 0-deg angle of attack from a detailed knowledge of the rocket attitude.

An ion mass spectrometer measures relative abundances of the ions it samples from the ionosphere but can be calibrated, as is described in the following, to give absolute ion concentrations. An in-flight calibration was done for the Explorer XXXI mass spectrometer by comparing the total ion current (the sum of all the peaks) with nearly simultaneously acquired electron density data from the Alouette III topside sounder satellite (6).[1] The Alouette II and Explorer XXXI satellites, launched piggyback into similar orbits, were less than 30 min. apart over a given latitude for the passes used in this calibration, and it is assumed that both satellites were measuring the same ionosphere for these calibrations. Comparisons were first made in regions of almost pure (>99 percent) H^+ of various concentrations up to 10^4/cc, then, in regions of greater than 95 percent) O^+ in the range of 10^2 to 5×10^5 ions/cc. Calibration curves for the two major constituents were thus produced as are shown in Fig.2. For the other ion species, calibration was done by interpolation. The overall precision of the measurements, after applying this calibration procedure, is of the order of 10 percent as is demonstrated by comparisons with other Alouette II data and the other direct measurements probes on the Explorer XXXI satellite (2).

Since data from a spin stabilized cartwheel orbit type of satellite, like Explorer XXXI, are highly roll modulated and only the ram position data are used, the spatial resolution of the data is of the order of 100 to 200 km for spin periods of 2 to 3 rpm. On an oriented satellite, such that the angle of attack is maintained near 0 deg, the spatial resolution would be the mass spectrum

[1] Underlined numbers in parentheses designate References at end of paper.

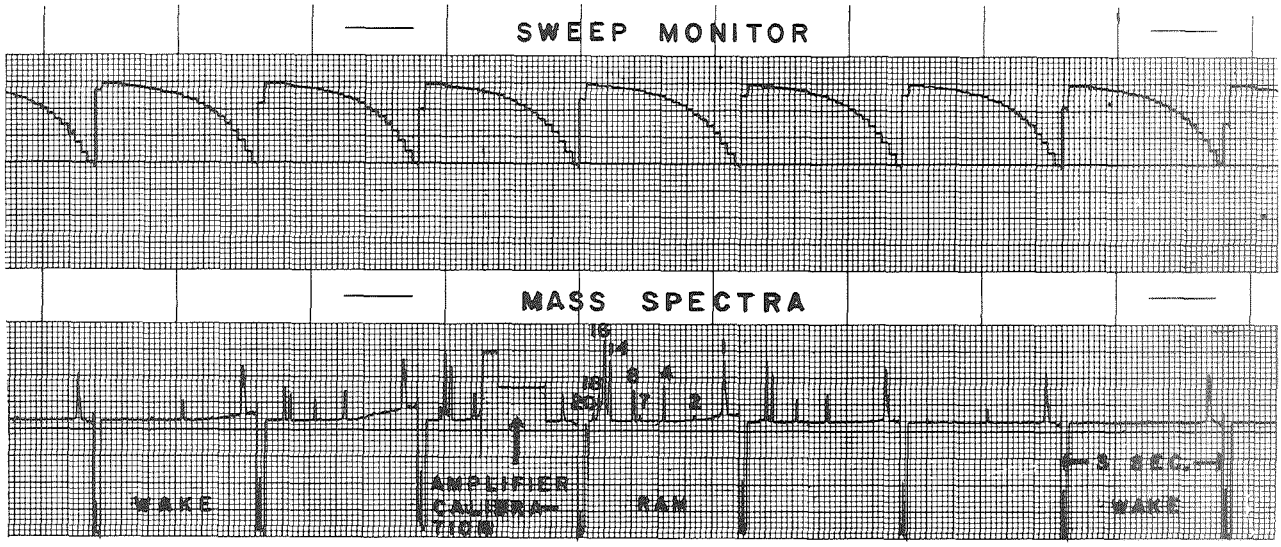

Fig.1 Portion of Explorer XXXI telemeter record showing sweep monitor in upper channel and mass spectrum below. Downward blips are markers showing recharge of high voltage sweep circuit. Note roll modulation of ion peak amplitudes (labeled in amu)

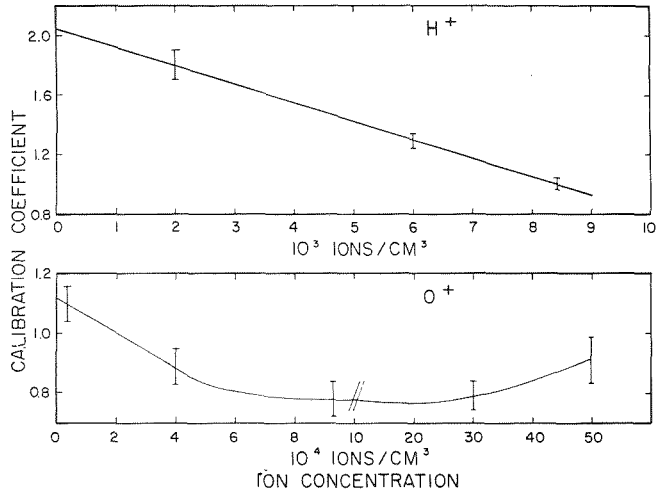

Fig.2 Calibration coefficients. Ratio of Alouette II electron density to H^+ and O^+ concentrations versus ion concentration. Note scale change in abscissa of O^+ curve

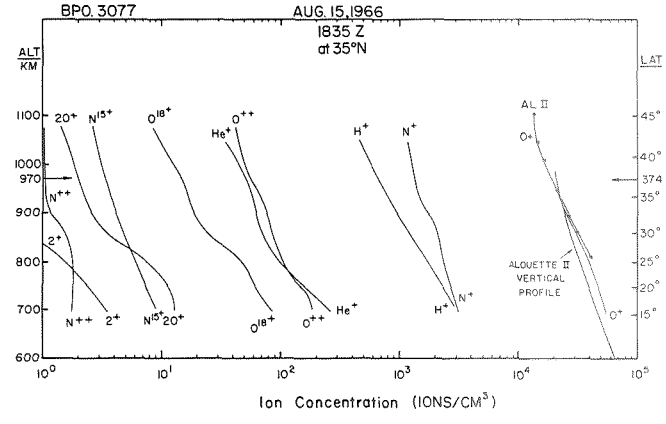

Fig.3 Typical low-altitude data showing ion concentration versus altitude and latitude. Ten different ion species are observed. Alouette II electron concentrations are also given

sweep period times the vehicle velocity, or from 6 to 20 km.

A magnetic deflection mass spectrometer exhibits good mass resolution and sensitivity as is evidenced by the Explorer XXXI data. Ten different ion species have been observed between 1 to 20 amu at 1(H^+), 2(D^+), 4(He^+), 7(N^{++}), 8(O^{++} or He_2^+), 14(N^+), 15(N_{15}^+), 16(O^+), 18(H_2O^+ or O_{18}^+), and 20(Ne^+) amu (5). All except mass 15 are shown in Fig.1. The sensitivity of the Explorer XXXI mass spectrometer to H^+ ions is of the order of 0.3/cc and to O^+ ions of the order of 10/cc.

A summary of recent scientific advances obtained with the magnetic deflection mass spectrometer follows. In general, it has been found from the Explorer XXXI data that below 1000 km O^+ is the dominant ion species in the ionosphere (Fig.3). N^+ varies from 5 to 30 percent of the O^+ and H^+ is generally a minor constituent, occasionally as low as 5 percent of the O^+ Above about 2000 km at mid to low latitudes, the ionosphere generally consists of the order of 99 percent H^+, the remainder being He^+, D^+, and 8^+. The crossover altitude between O^+ and H^+ is quite variable, being a function of several parameters. He^+ is a very minor constituent at all altitudes being of the order of a few percent to less than 1 percent.

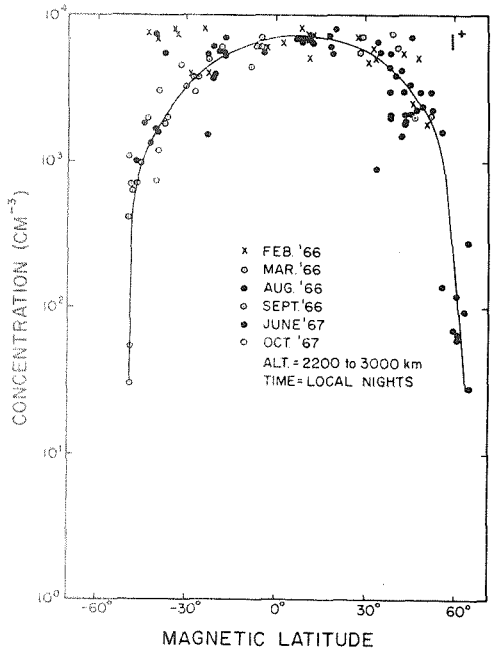

Fig.4 Distribution of H^+ ions above 2200 km as a function of geomagnetic latitude and season

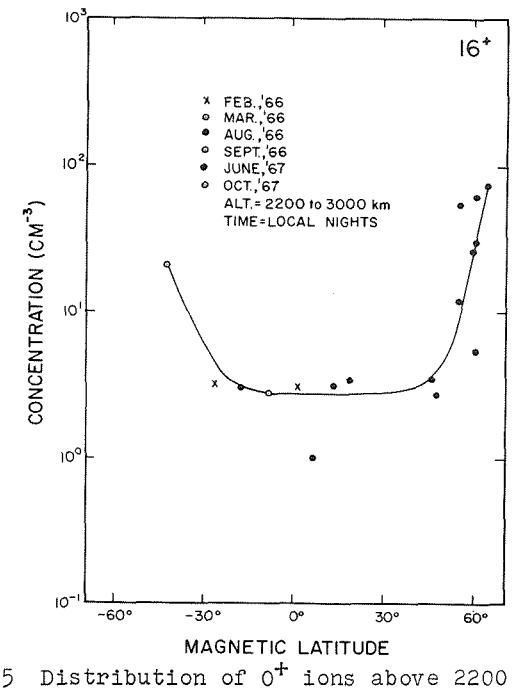

Fig.5 Distribution of O^+ ions above 2200 km as a function of geomagnetic latitude and season

An ion peak at mass 8 amu is frequently observed in the data, always at low altitudes and not infrequently above 2000 km. In regions where O^+ is the dominant constituent, the mass 8 ion is identified as O^{++}, formed by photoionization of O^+. Its relative abundance is of the order of a few x 10^{-3} of the O^+. Likewise, a peak at mass 7 is identified as N^{++}. These are the first data in which the doubly charged constituents have been observed. From 2200 to 3000 km, the mass 8 ion distribution, at a concentration of the order of 1/cc, favors the southern hemisphere in January and February, whereas in July and August, it is more equally distributed. O^+ is found above 2200 km only in the summer northern hemisphere and, then, almost always above 50 deg N geomagnetic latitude. On the other hand, He^+ appears at all times in both hemispheres.

At altitudes from 2200 to 3000 km, the concentration of H^+ and O^+, as a function of geomagnetic latitude and season, are shown in Figs.4 and 5, respectively. In the local summer, the concentration of H^+ decreases abruptly at about 60 deg, and the concentration of O^+ rises correspondingly making O^+ the dominant ion species. O^+ is seldom observed at these altitudes except in the regions around 60 deg and northward. These regions of O^+ dominance are not particularly structured in the summer, but the total ion concentration is almost two orders of magnitude below that at lower latitudes where H^+ is the dominant species.

In the winter polar region above 2500 km, O^+ has also been observed to become the dominant ion constituent in a highly structured narrow region between 75 and 85 deg N geomagnetic latitude. Fig.6 shows such a situation. The H^+ concentration exhibits 1 to 2 orders of magnitude trough at 70 deg N geomagnetic latitude, whereas the O^+ region lies to the north, but not to the south, of the trough. There is evidence from the phase difference of the maxima in the roll modulation curves (Fig.7) in this structured region and in the summertime regions of O^+ dominance, that H^+ ions are flowing upward with a velocity of 10 to 15 km/sec. This is the first experimental evidence for the polar wind (1).

An Argo (Javelin) rocket was launched from Wallops Island, Virginia at 1828 GMT, August 15, 1966, to rendezvous with a pass of the Explorer XXXI and Alouette II satellites. Identical magnetic mass spectrometers on the rocket and Explorer XXXI satellite measured the composition of the ionosphere, while the Alouette II topside sounder provided electron density profiles.

Data were obtained on the rocket flight from 425 km on the up-leg to the peak of flight, 723 km, and down to 130 km on the descent. Fig.8 shows a plot of the concentrations of each ion species as a function of rocket altitude with the direction of the arrows indicating up- or down-leg of the flight. The solid curve to the right in the figure shows the electron density measured by the Alouette II Topside Sounder (10) matched to the Wallops Island Ionosonde (9) data taken at the time of flight of the rocket.

The Explorer XXXI ion composition results,

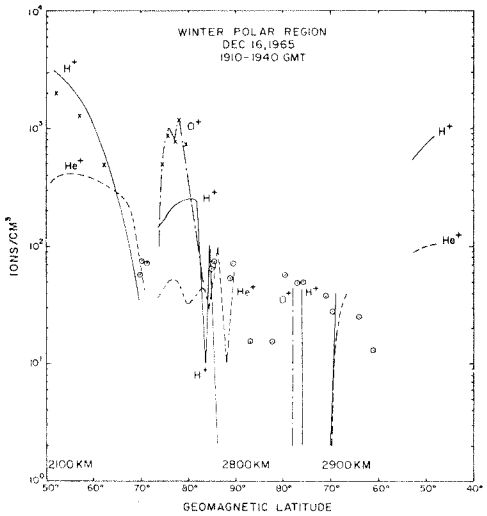

Fig.6 Ion concentrations versus geomagnetic latitude for northern polar region. X's are Alouette II data reduced by standard method. O's are Alouette II data by Hagg method. In region around 80 to 85 deg N, H^+ ions have an upward drift velocity of 10 to 15 km/sec. N^+ is also observed at concentration of 6 percent of O^+, (not shown in figure)

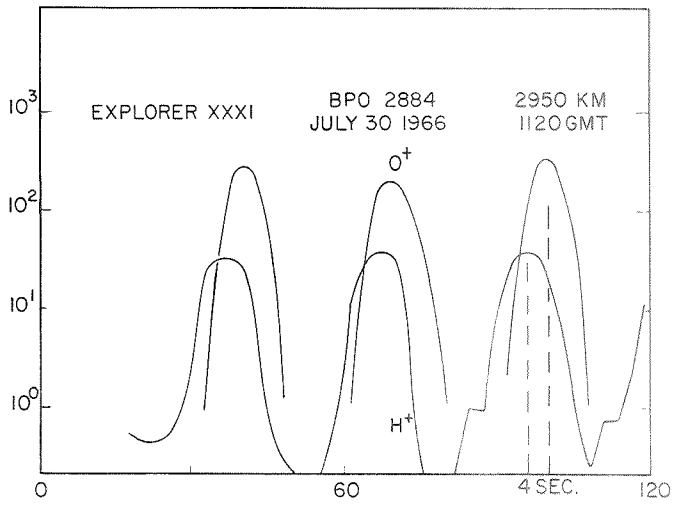

Fig.7 Ion concentration versus time showing phase difference in the roll modulation maxima of H^+ and O^+

plotted as a function of height, are shown at the top of the figure as dashed lines. The X's are the values at the intersection of the rocket and satellite trajectories.

The O^+ profile follows the Alouette II N(h) profile reasonably well. O^+ is by far the dominant constituent, being 94.2 percent (including 2.8 percent H_2O^+) of the total ion concentration at 700 km. N^+ is next at 4.1 percent, and H^+, being a very minor constituent, even at the satellite altitude, indicates that its crossover with O^+ lies well above 1000 km. A mass 8 ion is observed throughout the rocket data and is identified as O^{++}. Its scale height is very large (actually it is negative but could be infinite within the experimental error) indicating a doubly charged constituent of half the mean ion mass. It is unlikely that the mass 8 is He_2^+, since its concentration is greater than that of He^+. The very low He^+ concentration shown here, 0.15 percent, is typical of the He^+ values observed by the Explorer XXXI satellite in mid-latitude regions.

The molecular ion constituents, NO^+, O_2^+, and N_2^+ all have maximum concentration below the F_2 maximum. There is a significant change of slope in the NO^+ and O_2^+ at about 350 km, but not in the N_2^+ data. The data points below 200 km are subject to greater uncertainties than those at higher altitudes due to the increased rocket velocity and correspondingly greater roll modulation of the ion peak amplitudes. The rocket is also tumbling and, therefore, yields relatively few points when the angle of attack is sufficiently small to enable a roll modulation correction to be made. The result is that the altitude of the maxima of the molecular constituents may be in error by up to 30 km.

In the lower region of the ionosphere, H^+ and O^+ are in chemical equilibrium through the well-known charge exchange reaction (4),

$$\frac{n(H^+)}{n(O^+)} = \frac{9}{8}\frac{n(H)}{n(O)} \qquad (1)$$

Since equation (1) represents both the source and sink for H^+, the scale height of the ratio of $n(H^+)$ to $n(O^+)$ is characterized by an effective mass of 15 amu and is a function of the neutral gas temperature. From the observed scale height of 53 km', the temperature of the neutral gas is 940 K. It is assumed that $T_g = T_i$ here.

From a model of the neutral atomic oxygen distribution and with the aid of equation (1), the neutral hydrogen distribution can be calculated for the region of chemical equilibrium. The model atmosphere of Harris and Priester (1962) at a temperature of 962 deg and 10.7 cm flux of 100 x 10^{-22} W/sq m cps was used for the atomic oxygen profile which is shown in Fig.9. The measured oxygen values of Krankowsky, Kasprzak, and Nier (8) for a summer daytime rocket flight at White Sands are given as dots in the figure to which the Harris and Priester model n(O) was normalized at 200 km, the normalization constant being 0.77.

The calculated atomic hydrogen distribution from equation (1) and the n(O) curve is then given as the dashed curve in Fig.9. For comparison, the

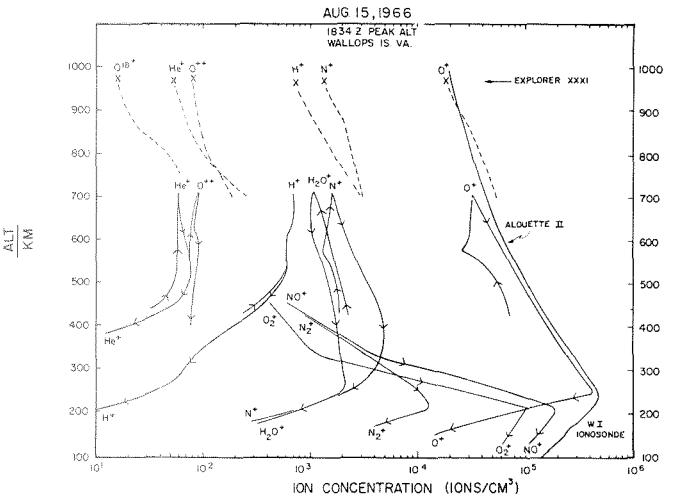

Fig.8 Ion concentration as a function of altitude showing both the rocket data (solid lines) and the satellite data (broken lines). X's refer to the satellite data at the point of intersection of the two trajectories. The Alouette II electron density from the topside sounder experiment is matched to the Wallops Island ionosonde data at the F2 maximum

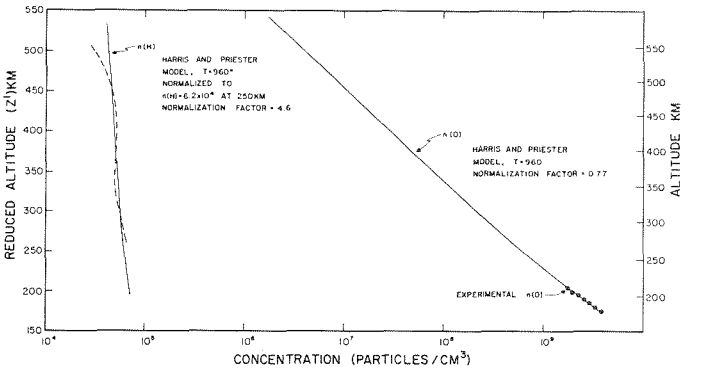

Fig.9 Concentrations of O and H as a function of reduced altitude. The model n(O) is normalized to a rocket measurement (see text) at 200 km. Calculated n(H) is the dashed curve. Model n(H) is normalized to calculated value at 250 km'. Normalization factor is 4.6

Harris and Priester model hydrogen profile is given as the solid n(H) curve normalized to the calculated n(H) at 250 km'. The normalization factor here is 4.6. The alculated values agree well with the model up to 450 km' where the significant departure indicates that the H^+ is no longer in chemical equilibrium with O^+.

Krankowsky, et al. quote a probable accuracy of 25 percent for the atomic oxygen number density; the $n(H^+)/n(O^+)$ ratio probable accuracy is 20 percent. Therefore, the n(H) probable accuracy is 45 percent.

The chemical equilibrium distribution of $n(He^+)$ produced in the atmosphere by the photoionization of neutral helium and lost by charge transfer with N_2 is given by

$$n(He^+) = \frac{I_{He}\ n(He)}{k\ n(N_2)} \qquad (2)$$

where I_{He}, the photoionization rate coefficient for He, is 1×10^{-7} sec^{-1}, and k is the rate coefficient for the loss process with N_2 given by Ferguson, et al. (3) to be 1.3×10^{-9} cc sec^{-1}. From the Harris and Priester model atmosphere used previously for n(O), the values of n(He) and $n(N_2)$ were found at 370 km', again having normalized the model curves to the data of Krankowsky, et al. at 200 km. In this case, the normalization factors were 0.7 for He and 1.2 for N_2. From the measured $n(He^+)$ at 357 km', 20 ions/cc, k is found to be 1.2×10^{-9} cc sec^{-1} in good agreement with Ferguson, et al. (3).

In comparing the present results with those of other mass spectrometer flights in a similar time period, it is seen that there is a difference in the $n(H^+)$ measurements, the present result being lowest. The in-flight calibration tends to indicate that a mass spectrometer is overly sensitive to light mass ions compared to O^+.

Presently, a second generation magnetic deflection mass spectrometer is being developed for ionospheric composition studies and will be flown on the ISIS-B satellite in 1971, and the AE-C and D satellites in 1973. It consists of a dual-channel analyzer set to simultaneously measure the 1 to 8 and 8 to 64 amu mass ranges, and a "Peaks" circuit which is an on-board computer that seeks the position and amplitude of each peak in the mass spectrum telemetering only this information at an order of magnitude saving in telemetry band width. The dual analyzer will provide an increased mass range, better resolution and sensitivity at the high mass end of the spectrum, and a sweep time of 1 sec per spectrum giving either increased spatial resolution or more precisely defined roll modulation of the data.

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