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POSITIVE ION COMPOSITION AND DENSITY IN THE LOWER E-REGION, FROM 87 TO 114 KILOMETERS

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ABSTRACT

A ceramic positive ion mass spectrometer of the Bennett type, mounted in an ejected payload package, was carried to 114 km above Wallops Island, Virginia, at midday in May 1962. Nitric oxide and molecular oxygen were the predominant ions measured in the 87 to 114 km altitude range. Near 100 km these ions were approximately equal in concentration. Above this altitude NO^+ increased in concentration to 113 km where it was 10^5 ions/cm^3, while the concentration of O_2^+ was 4×10^4 ions/cm^3. The concentration of each of the other ions observed, 24^+ and 28^+, was less than either of the predominant constituents. The ion 28^+, identified as molecular nitrogen and/or silicon, was observed between 103 and 114 km, and reached a peak density of 10^4 ions/cm^3 at 113 km. The ion 24^+, identified as magnesium, exhibited two distinct layers of concentration, the lower near 93 km and the upper at 113 km; the maximum concentration of this ion was 1.5×10^3 ions/cm^3. The total ion density varied from approximately 4×10^3 ions/cm^3 at 90 km to 10^5 ions/cm^3 at 110 km. This measurement showing that NO^+ and O_2^+ are of approximately equal concentration in the lower E-region compares favorably with similar measurements made by other investigators; the significance of this result is examined in the light of current theories which treat the relative importance of NO^+ and O_2^+ and the removal of N_2^+ ions in this region.

Author

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INTRODUCTION

An Iris rocket, NASA 5.04, was launched into the ionosphere above Wallops Island, Virginia, at 1830 GMT on May 3, 1962, carrying a ceramic Bennett rf ion mass spectrometer calibrated to measure thermal positive ions from 7 to 43 amu. The objectives of this flight were to measure ion composition in the upper E and F-regions using a payload separated from the rocket motor and to obtain a flight test of a new ceramic spectrometer similar to the one being prepared for flight on the Orbiting Geophysical Observatory series.

As a result of reduced rocket performance the payload trajectory was considerably lower than that obtained in previous flights of the ion spectrometer. Accordingly, a more thorough observation of the ion composition of the lower E-region was made possible. The purpose of this paper is to present the detailed results of this measurement in the altitude range 87-114 km and to examine the meaning of these results in terms of current theories of the atmosphere and similar measurements.

PAYLOAD INSTRUMENTATION

A primary feature of the instrumentation was the payload separation device designed to eliminate possible background contamination associated with rocket outgassing. Pyrotechnically released spring actuators were used to place the payload sufficiently distant from the rocket motor that collisions with the ambient atmosphere would prevent a contaminant molecule from reaching the orifice of the spectrometer. The absence of spurious trace constituents from the data indicates that the payload separation was successful in eliminating contamination.

The separated instrumentation package consisted of an ion mass spectrometer, roll and yaw magnetometers, an optical aspect system, and supporting electronics. The sensor, a ceramic spectrometer tube, has previously been described in the literature [Taylor, Brinton, and Smith, 1962]. The spectrometer was mounted in the payload with its long axis coincident with the rocket spin axis. The orifice and guard ring, located on the forward end of the payload, are shown in Figure 1. The spectrometer and associated instrumentation details are discussed more fully in Appendix 1.

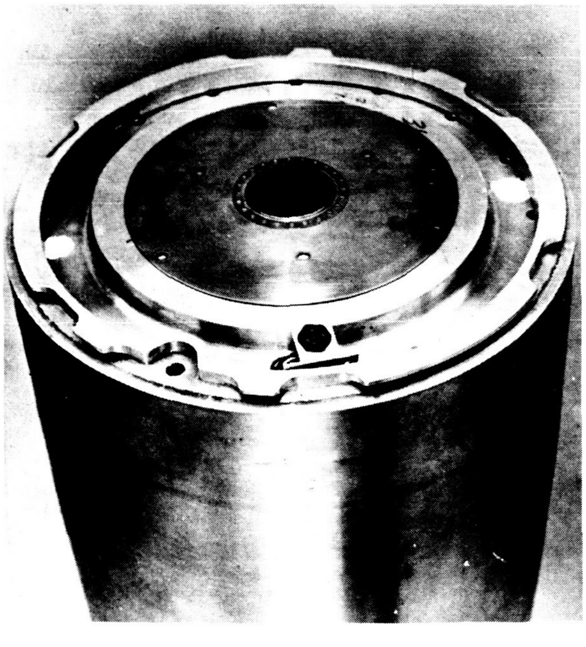

Figure 1—End view of the NASA 5.04 payload instrumentation section showing guard ring and spectrometer orifice grid.

RESULTS

1. Ion Current Data

A total of 70 complete ion spectrums were recorded in the altitude range of 87-114 km, providing a high resolution sampling of the positive ions in the lower E-region. Four ions were detected during the flight, 30^+, 32^+, 24^+, and 28^+, identified as nitric oxide, molecular oxygen, magnesium, and silicon or molecular nitrogen, respectively. A typical spectrum recorded when the payload was near peak altitude is shown in Figure 2.

An example of the raw ion current measured at the collector of the spectrometer is shown in Figure 3, a plot of NO^+ ion current versus altitude. The spread in the raw data points is primarily a result of aspect variation during the flight. A smooth curve representing the average of ascent and descent data has been derived to provide an altitude profile. A similar procedure has been used to obtain altitude profiles for the remaining ion constituents. The conversion of these ion current profiles to profiles of ion density is discussed in detail in Appendix 2.

2. Ion Composition

The predominant ions measured throughout the altitude region from 87 to 114 km were nitric oxide and molecular oxygen. As shown in Figure 4, NO^+ and O_2^+ were of approximately equal concentration near 100 km. Above 100 km NO^+ gradually increased in concentration until at peak NO^+ exceeded O_2^+ by a factor of three. Based on the normalization technique described in Appendix 2, the concentration of NO^+ at 113 km was 10^5 ions/cm^3 and O_2^+ was 4×10^4 ions/cm^3.

The ions, 24^+ and 28^+, were at all times of lower concentration than either 30^+ or 32^+. Mass 28^+, first detected by the spectrometer at 103 km, was observed to increase in amplitude, reach a peak density near 113 km, and then

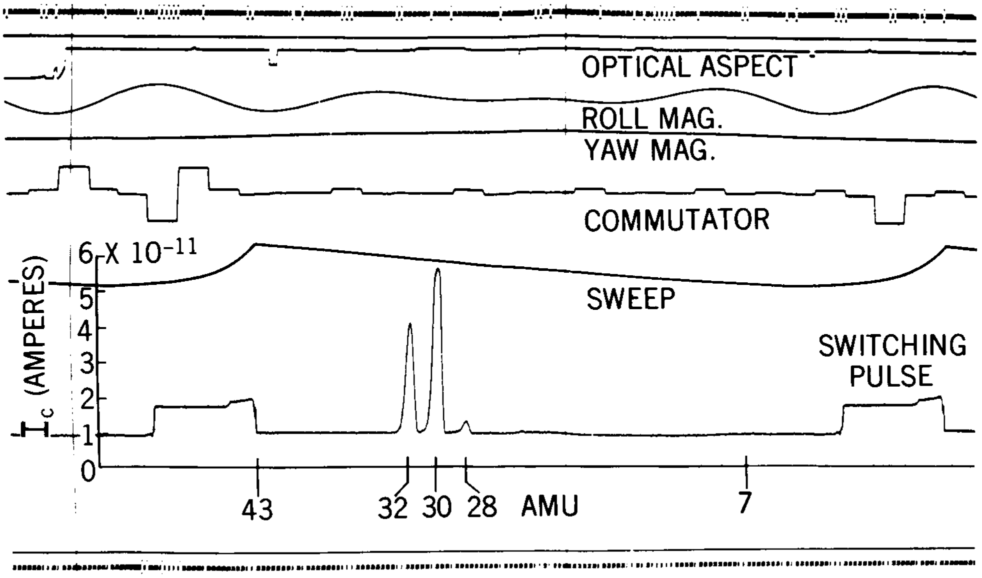

Figure 2–Section of telemetry record showing typical ion mass spectrum.

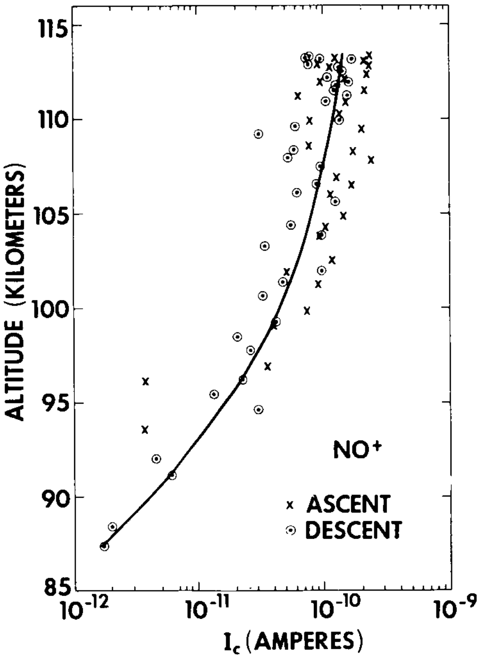

Figure 3–Nitric oxide ion current data normalized to a constant spectrometer sensitivity. A smooth curve representing the average between ascent and descent data is drawn through the points. The spread in the points is indicative of aspect variation throughtout the flight.

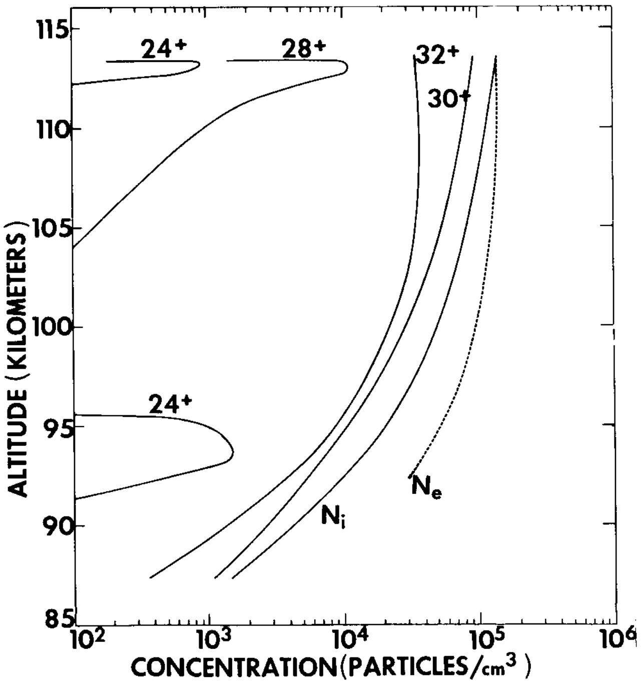

Figure 4–Individual and total ion concentration distributions obtained by normalization of total ion current measured at 113 km to electron density at that altitude. The electron density profile obtained by ionosonde is also shown.

drop sharply near peak altitude. Mass 24^+ was found in two distinct layers of concentration. The first layer was found to peak near 93 km with a thickness of 5 km. The second layer, near 113 km, was found to be thinner than the lower altitude layer and also slightly less dense. The maximum density of 28^+ was 10^4 ions/cm^3 and 24^+ approximately 1.5×10^3 ions/cm^3.

INTERPRETATION

1. The Major Constituents, 30^+ and 32^+

One of the most significant results of these data is the observation that NO^+ and O_2^+ are of approximately equal concentration in the lower E-region. This is in agreement with ion spectrometer measurements made during periods of low solar activity [Johnson, 1966]. Ion composition data obtained in the D-region [Narcissi and Bailey, 1965] indicate a predominance of NO^+ over O_2^+ with O_2^+ increasing in concentration until their detector became saturated, thus limiting their measurement above 83 km. In further interpretation of their data Narcissi and Bailey [AFCRL-65-81, 1966] provide an estimate of the NO^+/O_2^+ ratio near 100 km and indicate that NO^+ and O_2^+ were of equal concentration.

Measurements of solar flux at solar minimum in the region 83-93 km [Bourdeau, Aiken, and Donley, 1966] indicate ionization by 2-8Å X-radiation and the C VI line at 33.7Å producing O_2^+ and N_2^+. These ions are transformed into NO^+ by the following charge transfer and/or ion - atom interchange processes:

$$N_2^+ + O_2 \rightarrow O_2^+ + N_2 \qquad (1)$$

$$O_2^+ + N_2 \rightarrow NO^+ + NO \qquad (2)$$

and the process involving reactions 1 and 2

$$N_2^+ + O_2 \rightarrow O_2^+ + N_2 \rightarrow NO^+ + NO \qquad (3)$$

resulting in the predominance of NO^+ in this region. This predominance below 100 km can be seen in our data presented in Figure 4.

In the region from 93-115 km, where NO^+ and O_2^+ can be nearly equal in concentration, Bourdeau et al. [1966] show the principal ionizing agents to be EUV and 40-75 Å radiation producing O_2^+ and N_2^+, respectively, with the production of N_2^+ being less than O_2^+. They further state that the exact ratio of these ions depends upon the O/O_2^+ ratio.

It is likely that N_2^+ ions are removed from this region by reaction 3 and the reaction

$$N_2^+ + O \rightarrow O^+ + N_2 . \qquad (4)$$

These reactions are thought rapid enough to be the essential loss processes of N_2^+ in the D and E-regions [Nicolet and Swider, 1963; Nicolet, 1965].

2. The Minor Constituents, 24^+ and 28^+

The ion 24^+, identified as magnesium, was one of the two minor ions detected during this flight. Istomin [1963] was the first to observe the magnesium isotopes, 24^+ and 26^+, on a rocket flight using a Bennett spectrometer. These isotopes were observed in two stratified regions, one at 105 km and the other at 120 km, and were thought to be of meteoric origin. Ions of calcium, 40^+, and iron, 56^+, ascribed to the same source, were detected at 105 km. Narcissi and Bailey [1965] also detected metallic ions during a recent flight of their quadrupole spectrometer. In contrast to Istomin's data they found these ions to occur at the somewhat lower altitude of 95 km; in addition there was an indication in their data of a rapid increase in metallic ion concentration at peak altitude, 112 km. Furthermore, they observed sodium ions, 23^+, and what is believed to be a third isotope of magnesium, 25^+. Hunten [1964] has observed sodium in twilight and dayglow emissions in this region and attributes it to marine origin.

Our measurement of Mg^+ is in general agreement with the results of Narcissi and Bailey. As shown in Figure 4, Mg^+ exhibited two distinct layers of concentration, one occurring at 93 km and the other at 113 km. The higher altitude layer coincides with the sharp increase in ion current observed at 110 km by Narcissi and Bailey. However, the Mg^+ detected at 93 km on the 5.04 flight is approximately a factor of five lower in density than their reported peak concentration of 6×10^3 ions/cm^3 for this ion. This difference could explain why the magnesium isotopes 25^+ and 26^+ were not observed on the 5.04 flight, since if they occur in their natural abundances, the limiting sensitivity of our spectrometer might have prevented their detection. There is no explanation, however, why the ions Na^+ and Ca^+ were not detected if they were present in the quantities indicated by Narcissi and Bailey. We can only conclude that during this flight they did not occur in any appreciable quantity.

The ion 28^+, identified as N_2^+ and/or Si^+, was the other minor ion detected. As shown in Figure 4, 28^+ reached a peak abundance at 113 km, being 10% of the total ion density at this altitude. Istomin [1963] reported 28^+ at 105 km and 120 km and gave an abundance for the lower layer which is comparable in magnitude to that of the single layer observed on this flight. Narcissi and Bailey [1965] were not able to resolve 28^+ in their data because of the predominance of NO^+.

The true identity of 28^+ is a matter for speculation since it was not possible for our spectrometer to distinguish between N_2^+ and Si^+. If this ion is N_2^+ it is difficult to understand why it occurs in such abundance, since it is believed that reactions involving N_2^+ proceed with great rapidity (see equations 1, 3, and 4) and result in the removal of N_2^+ from this region of the ionosphere. If this is the case, the logical identity of 28^+ would be the metallic ion, Si^+. As shown in Figure 4, the 28^+ profile has several features in common with the Mg^+ profile. The 28^+ peak occurs at precisely the same altitude as the upper Mg^+ layer and shows the same reduction in density above that region. The argument for the identification of 28^+ as silicon may be slightly weakened since it did not appear with Mg^+ in the 93 km region.

The stratification of the metallic ions may possibly be caused by wind shears which are known to occur in this altitude region [Donahue, 1966]. A number of both ascent and descent data points define the strata shown, thus giving confidence to their existence.

3. Total Ion Density Distribution

The total positive ion density distribution shown in Figure 4 begins to deviate significantly from the electron density profile below 105 km. Although this deviation may be due in part to a mean free path limitation, it is presumed to be caused primarily by inaccuracies in the ionosonde electron density values obtained in the low altitude region. The total ion density at 90 km is 4×10^3 ions / cm^3, a value which agrees with the results of Bourdeau, Aikin, and Donley [1966].

CONCLUSIONS

As a result of considering the data obtained on this flight and comparing it with the measurements of other investigators, the following conclusions concerning the composition of the lower E-region may be drawn.

1. Nitric oxide and molecular oxygen are the predominant ions in the altitude region from 87 to 114 km and are approximately equal in concentration near 100 km.

2. Molecular nitrogen ions and/or silicon ions do not occur in appreciable quantities below 110 km, however, a layer of 28^+ at 113 km is believed attributable to silicon.
3. Magnesium ions are found in stratified regions occurring at 93 and 113 km.
4. The ion density varies from approximately 4×10^3 ions / cm^3 at 90 km to 10^5 ions/cm^3 at 110 km.

APPENDIX 1

THE ION SPECTROMETER

INTRODUCTION

The spectrometer tube consists of a stack of planar gold-plated tungsten mesh grids separated by precision cylindrical ceramic rings fused in a single brazing operation. Although the materials and construction techniques have been significantly changed, the physics and electrical operation of the spectrometer were similar to those of Bennett spectrometers flown on several rockets [Taylor and Brinton, 1961; Taylor, Brace, Brinton, and Smith, 1963]. Ceramic ion spectrometers have since been flown on the OGO I [Taylor, Brinton, and Smith, 1965] and OGO II satellites.

OPERATION

The theory of the Bennett rf spectrometer has been discussed extensively in the literature [Bennett, 1950; Johnson, 1960] and therefore will not be presented here. However, the mode of spectrometer operation and the effects of the guard ring G_1 voltage and the stopping potential V_s will be discussed to permit a better evaluation of the data. For this flight a three-stage 7-5 cycle, 3 mm tube operating at a frequency of 4 Mc was used. The accelerating potential V_a was swept to provide a mass range from 7 to 43 amu, with a resolution of 1 in 20. A 1.4 second sweep period provided an average spatial resolution for all masses of 0.5 km.

The guard ring, an external plate and grid assembly placed in front of the spectrometer orifice, is shown in Figure 1. Its function was to provide a uniform electric field in the orifice area and to increase the ion attraction capability of the spectrometer. The negative dc voltage, G_1, applied to the guard ring was stepped to a new value at the end of each sweep through a series of three levels, -20, -10, and 0 volts. This changing drawing-in potential produced a maximum variation in sensitivity of approximately a factor of three during the flight.

The V_s is a positive dc potential which is applied to three adjacent grids following the last analyzer stage in the spectrometer. This voltage was stepped to a new value at the end of each sweep cycle through a series of four levels. Its purpose is to permit only selected ions to reach the collector, and thus it regulates the sensitivity of the spectrometer. It should be noted that all ion data presented in this paper have been normalized to the same V_s, G_1 combination, and hence represent measurements at constant spectrometer sensitivity.

APPENDIX 2

CONVERSION TO ION DENSITY

INTRODUCTION

The direct conversion of measured ion currents to ambient ion densities is extremely difficult. The desired results are dependent upon a correct evaluation of the factors involved in the interaction of the vehicle and the ionized atmosphere [Bourdeau, 1962-3]. These factors, which influence the overall sensitivity and efficiency of the instrument, at present are not subject to definition by direct measurements. For this reason it is believed that the most reliable presentation of ion concentration data can be obtained by normalizing spectrometer measured ion currents to the electron density measured by ionosonde techniques during the flight. To compare the results of this normalization and the direct conversion technique, a density calculation was performed using an ion current measured at 112 km. The results of the normalization are shown in Figure 4. The method of normalization and the equation for direct conversion are presented in the next two sections.

DIRECT CONVERSION

When the angle between the spectrometer axis and the vehicle velocity vector is small (< 45°) the following equation may be used to directly convert from measured ion current to ambient ion density:

$$I_c = \alpha N e A V_r \cos \theta$$

where

I_c = measured ion current

α = spectrometer efficiency

N = ambient ion concentration

e = electronic charge

A = effective spectrometer orifice area

V_r = vehicle velocity

θ = angle between the spectrometer axis and the vehicle velocity vector

A calculation using this equation for O_2^+ at 112 km was performed and a value of 8×10^4 ions/cm^3 was obtained for the O_2^+ concentration at this altitude. This value was within a factor of two of that obtained by the normalization technique. The component of vehicle velocity along the spectrometer axis exceeded the estimated thermal ion velocity by a factor of two. The spectrometer efficiency factor (α) was determined by laboratory calibration. Since the ion current value used in the equation was measured with the guard ring at 0 volts, an effective spectrometer collection area equal to the size of the orifice was assumed. Effects due to rocket potential were not taken into account, since there is no evidence that a significant potential existed during the flight. Determination of the instantaneous angle θ was made difficult due to the precession of the payload with a half-angle of approximately 35° and a three second period. This motion resulted from forces arising during the nose cone and payload separation sequence and its analysis was complicated by partially ambiguous data obtained from the magnetometers and optical aspect sensor.

NORMALIZATION TECHNIQUE

The ionosonde electron density profile obtained at Wallops Island during the flight is plotted in Figure 4 along with the derived total ion density profile and the concentration distribution for each ion constituent. The individual ion profiles were derived by first normalizing the total ion current measured by the spectrometer at 113 km to the electron density at that altitude. This point normalization of the total ion current profile produced the total ion density distribution shown in the figure. The altitude profiles of individual ions were then obtained by dividing the total ion density distribution according to the relative ion currents measured for each constituent. Thus the shape of the density distribution obtained for NO^+ is identical to the ion current profile shown in Figure 3.

The validity of this normalization technique is based on four assumptions:

1. The ionosonde election density value used for normalization accurately reflects the ambient electron density at the point of normalization in the E-region.

2. The total number of electrons must equal the total number of positive ions at any altitude throughout the region of normalization.

3. The ratio of the ion currents measured at the spectrometer collector must accurately reflect the corresponding ratio of ambient ion concentrations.

4. The sum of the individual ion densities presented in Figure 4 must equal the total positive ion concentration in the ionosphere.

Uncertainty in the ionosonde electron density calculations results from ionization below the lowest altitude of reliable ionosonde measurements – in this case the altitude corresponding to 1.6 Mc, the lowest frequency at which observations were made. This inaccuracy is greatest below 105 km where the electron density gradient is steep. Our normalization was made at 113 km, near E-max at 116 km. In this region the gradient is small and the ionosonde inaccuracies should be minimal. It is accepted that the total number of positive ions is equal to the total number of electrons in the daytime E-region [Nicolet and Aikin, 1960], since the formation of negative ions occurs principally at nighttime in the D-region. The predominant ions measured during this flight were of approximately the same mass, thereby minimizing mass discrimination effects and preserving the ratios of ambient to measured ion concentrations. The absence in this region of significant quantities of ions beyond the detection range of this instrument, 7-43 amu, is supported by other measurements. Istomin [1961] found hydrogen and helium to be minor ions in the lower E-region. Data of Taylor, Brace, Brinton, and Smith [1963] show a sharp decrease in the light ions below 400 km. Measurements in this altitude region covering the ion mass range to 62 amu have been reported by Istomin [1963], who detected iron ions (56^+) in amounts comparable to magnesium (24^+) measured on the same flight. Since the latter was found to be a minor constituent in our data, we assume that any unmeasured contribution from 56^+ is small, and hence would only slightly modify the total ion density profile in Figure 4.

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