

LATITUDINAL VARIATION OF THE COMPOSITION OF THE  
TOPSIDE IONOSPHERE; FIRST RESULTS OF THE  
OGO-2 ION SPECTROMETER

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ABSTRACT

Direct measurements of a pronounced latitudinal variation in the exospheric ion composition have been obtained from the radio frequency ion spectrometer experiment on the Polar Orbiting Geophysical Observatory (OGO-2). Measurements of thermal positive ions obtained in a nearly polar dawn-dusk orbit during mid-October, 1965, show that in the altitude range of 415 to 1525 kilometers the major ions are  $O^+$  and  $H^+$  and the minor constituents are  $N^+$  and  $He^+$ . Consistent with this period of low solar activity  $He^+$  is at all altitudes a minor ion, relative to  $H^+$ . Evidence of pronounced solar and geomagnetic control of the ion distributions is further examined by translating the data along magnetic field lines to both (1) a constant 1000 kilometer reference level and (2) the dipole equator, applying chemical and diffusive equilibrium theory. At 1000 kilometers  $O^+$  dominates in both the northern and southern polar ionospheres, yielding at lower latitudes where  $H^+$  dominates. The resultant mean ion mass distribution, about 14 to 16 AMU at the

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poles, and about 4 AMU at the equator, is generally consistent with theory and other measurements. The latitudinal asymmetry in the distributions of  $O^+$  and  $N^+$  reflects the control of seasonal temperature differences, while the greater symmetry in the distributions of  $H^+$  and  $He^+$  reveals the strong influence of solar-geomagnetic control of the light ions. The high latitude ionosphere is marked by two dominant features: (1) a persistent, major trough in  $n(H^+)$  and  $n(He^+)$ , where  $n(H^+)$  drops to about  $10^2$  ions/cm<sup>3</sup> near 60 degrees dipole and (2) a variable poleward peak in which the total ion concentration,  $N_1$ , approaches  $10^4$  ions/cm<sup>3</sup> near 80 degrees dipole. The pronounced light ion trough, which correlates well with the whistler cutoff, is believed to mark the high latitude boundary of the thermal plasma which diffuses upward along closed field lines to populate the plasmasphere. Poleward of the trough, the strong fluctuations in the composition and the variability of the amplitude and position of the ionization peak suggest that the polar exosphere is decoupled from the plasmasphere and is probably linked with the solar wind-magnetospheric tail system. Comparison of the extrapolated equatorial  $N_1$  profile with thermal ion distributions measured directly in the magnetosphere further supports this interpretation.

## INTRODUCTION

### Background

Since the launch of the first artificial satellite, a number of direct and indirect observations have been made to describe the composition and distribution of thermal ions in the earth's atmosphere. Studies conducted using plasma probes, topside sounders, ion spectrometers, and whistler data, have contributed to a very useful although incomplete model of the upper ionosphere.

In 1958, Sputnik-3 carried an ion spectrometer which provided a limited study of the heavier ions, above 10 AMU, which were observed to increase in concentration with increasing latitude [Istomin, 1966]. Following this, the plasma probe aboard Ariel-1 provided a limited resolution study of the primary ion content, indicating significant latitudinal variation in  $O^+$  and  $He^+$ , and suggesting marked geomagnetic control of the composition [Bowen et al., 1964]. Still later, studies of the ionosphere by Alouette [Thomas et al., 1966], [Barrington et al., 1965] and by proton whistlers [Shawhan and Gurnett, 1966] further indicated a strong latitude dependence in the ion distributions.

In October 1965 the flight of a Bennet rf ion spectrometer on the OGO-2 satellite provided high resolution direct measurements of the total ion composition in the initial dawn-dusk orbit. This flight, which permitted a complete latitudinal sampling of the composition, has shown that the topside ionosphere consists of four significant ions,  $O^+$ ,  $H^+$ ,  $He^+$  and  $N^+$ , and that contrary to some previous assumptions,  $N^+$  is an

important constituent of the upper ionosphere. This paper presents the first detailed description of the latitudinal variation of the ion composition, and provides evidence of strong solar and geomagnetic control of the topside ionosphere and plasmasphere.

### The Experimental Equipment

The positive ion spectrometer on OGO-2 measured ambient thermal ions in the mass range 1 to 45 AMU. The Bennett rf spectrometer provided a dynamic sensitivity range of approximately  $1 \times 10^1$  to  $1 \times 10^6$  ions/cm<sup>3</sup> with a resolution of approximately 1 in 20 AMU. The spectral sweep rate, or time between consecutive samples of each ion detected, was 25.6 seconds which corresponds throughout the OGO-2 orbit to a spatial resolution of about 175-200 kilometers along the orbital path, or 1.5 degrees of latitude. The instrumentation, which consisted of a single 5-3 cycle Bennett spectrometer tube and associated electronics, was very similar to that flown on the OGO-1 satellite and described in more detail elsewhere [Taylor et al., 1965], [Brinton et al., 1968].

### Location of Observations

The pertinent elements of the OGO-2 orbit are given in Figure 1. During October 1965, the orbit was inclined near 87 degrees, with a perigee of about 415 kilometers and an apogee of about 1525 kilometers. The orbit period was approximately 104 minutes. The observations reported here were obtained from 14 to 24 October 1965, when the operation of the attitude control system of OGO-2 permitted acquisition of optimum data. During this interval the orbit plane was closely aligned

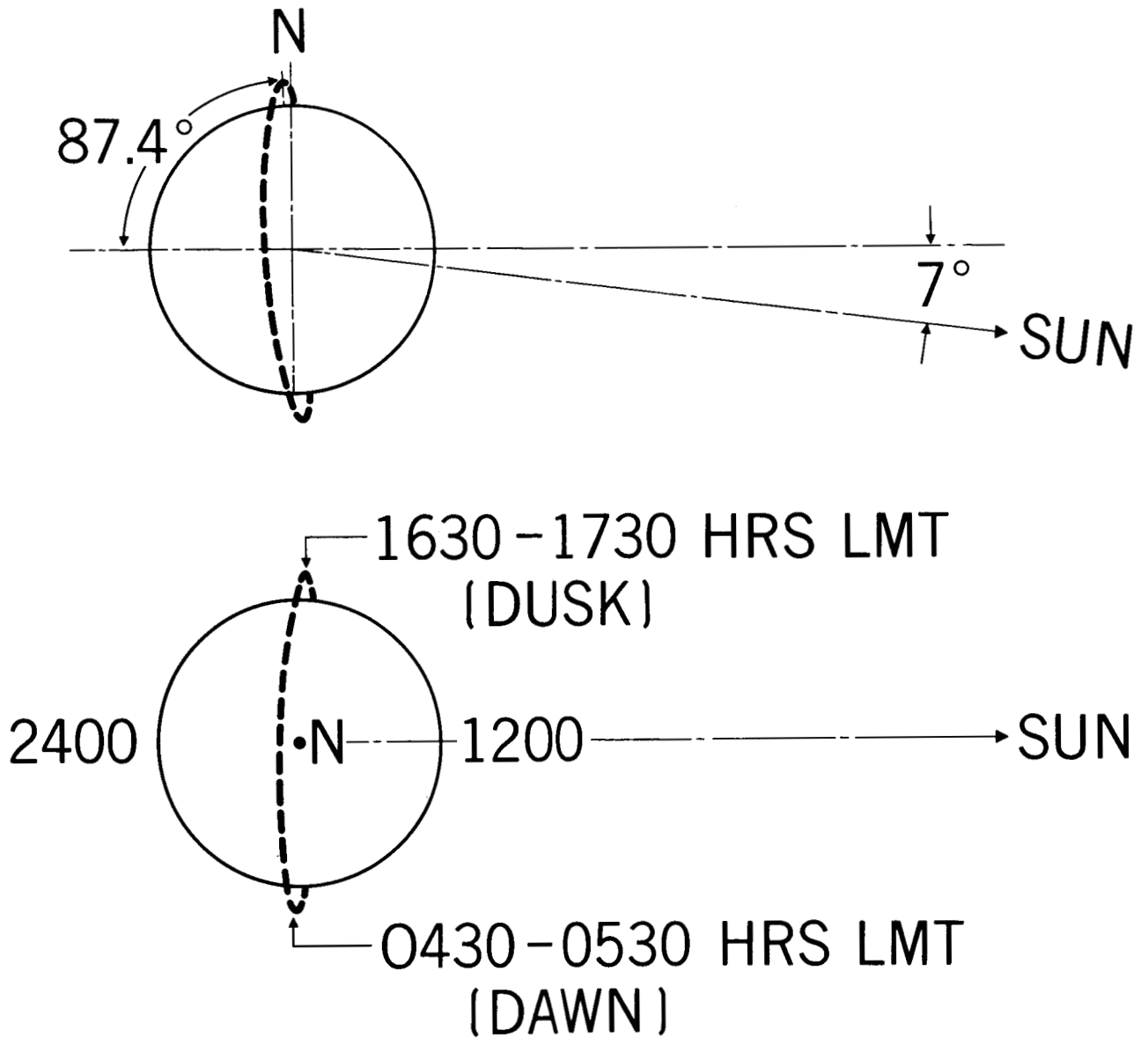


Figure 1. Characteristics of the OGO-2 orbit during the period October 14-24, 1965. Apogee: 1523 Km; Perigee: 415 Km; Inclination:  $87.4^\circ$ ; Period: 104 min.

with the 05:00-17:00 hours local-time plane, resulting in a dawn-dusk dependency in the observations. Unfortunately, the difficulties encountered with spacecraft attitude control were often severe and frequently interrupted many otherwise useful orbits, particularly near the dawn meridian. Accordingly, we have limited the results shown here to several complete latitude profiles for which the spacecraft attitude was least disturbed. These data, obtained on October 15, 1965, during low magnetic activity ( $K_p \leq 1$ ) illustrate the overall features of the composition, which were observed consistently during the 10 day period. Variations in the composition observed on later orbits, which occurred during enhanced activity ( $K_p = 3-5$ ), are also described.

On October 15, perigee was located on the dawn side of the orbit at about 10 degrees geographic latitude. Thus, allowing for the displacement of the dipole axis, the variation of altitude versus dipole latitude is nearly symmetric about the equator. Accordingly, for the orbits to be discussed, latitude variations are least confused by simultaneous altitude variations. During one day the precession of the orbit relative to the sun introduced minor local time variations between the orbits.

## RESULTS

### Ion Composition

The global distribution of the ion composition observed between 01:11 and 02:56 UT on October 15, 1965 is given in Figure 2. The ion concentrations are plotted versus dipole latitude to emphasize the geomagnetic control evident in the results. Throughout the altitude range

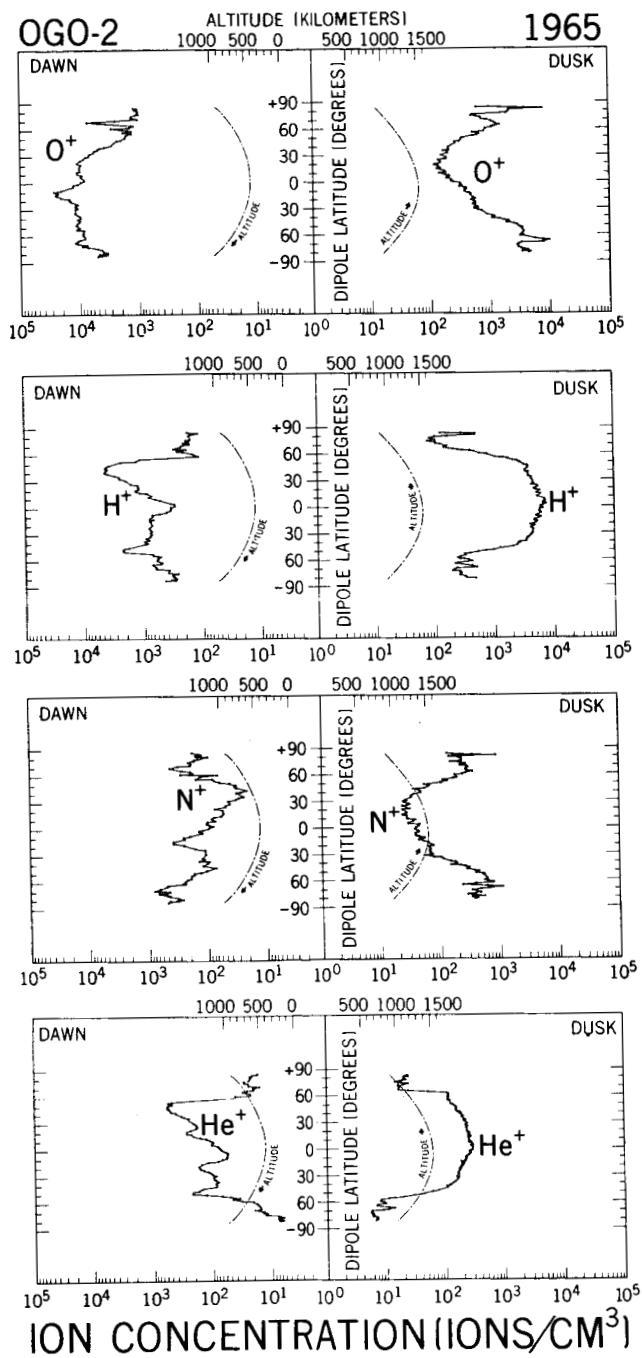


Figure 2. Concentrations of  $H^+$ ,  $O^+$ ,  $N^+$  and  $He^+$  as a function of dipole latitude. Orbit begins near  $85^\circ$  N (dawn) at 01:11 UT and ends near  $85^\circ$  N (dusk) at 02:56 UT on 15 October 1965. Consecutive data points are separated along the orbital path by about 175 kilometers and 1.5 degrees latitude. Direction of satellite motion is indicated along dot-dashed altitude curves.



of 415 to 1525 kilometers, the ionosphere is composed of four significant ions,  $O^+$ ,  $H^+$ ,  $He^+$  and  $N^+$ . Trace constituents such as  $NO^+$ , which were only occasionally observed, are not considered in this report.

The data of Figure 2 reveal several broad features which persist in the composition of the dawn-dusk ionosphere. First, at dusk, there is a distinct pattern of heavy ions dominating toward the poles and light ions prevailing at the equator. While this pattern is not as apparent near dawn, it will be shown in a later section, that upon elimination of altitude variation, the dawn and dusk distributions are quite consistent in this respect. Second, both the dawn and dusk ion distributions exhibit pronounced high latitude variability. Near 60 degrees, north and south, significant depletions occur, particularly in the light ion concentrations, and poleward of this region, the composition is marked by rapid fluctuations wherein the concentration of an ion may change by a factor of 5 within 1.5 degrees or 175 kilometers.

The persistency of these principal features of the composition is illustrated in Figure 3, which gives dawn and dusk ion distributions obtained from additional orbits covering the periods 23:25 to 01:11 UT on October 14-15 and 03:44 to 05:30 UT on October 15. The remarkable degree of latitudinal symmetry exhibited particularly in the  $H^+$  and  $H_e^+$  distributions is repeated throughout the 10 day period. Also, as indicated above, the pattern of heavy ions dominating at high latitudes and light ions prevailing at the equator is a persistent characteristic of the data. In contrast to the persistency of these features, however, important short

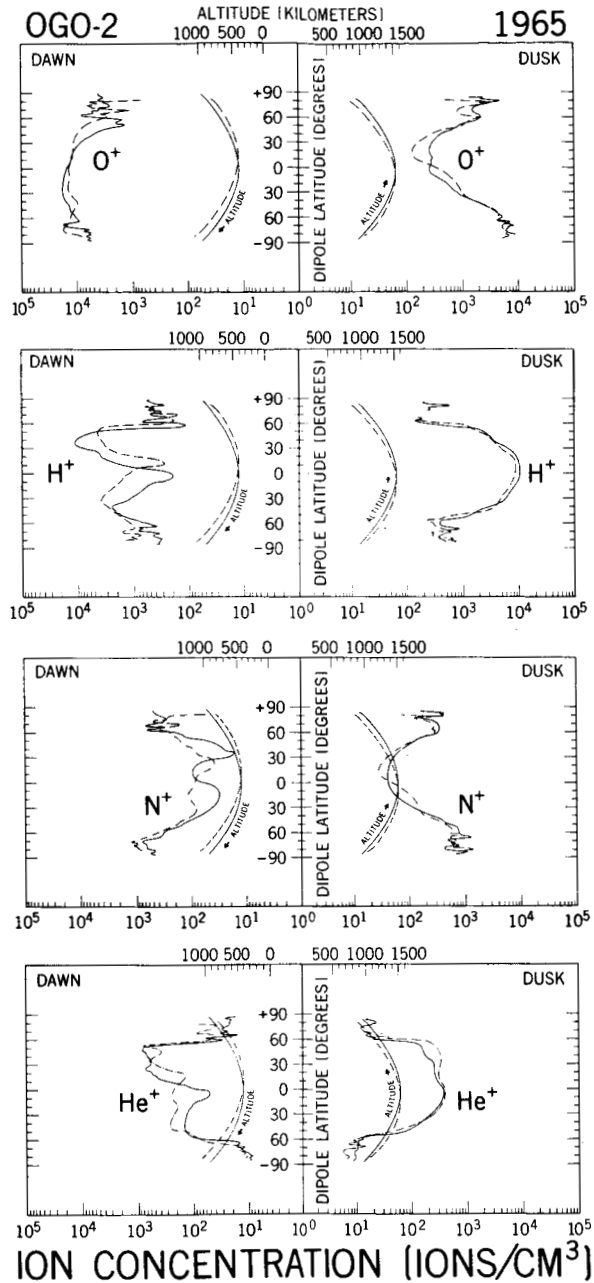


Figure 3. Concentrations of  $H^+$ ,  $O^+$ ,  $N^+$  and  $He^+$  observed on two additional orbits on 14-15 October 1965. Orbit 1 (solid curves) begins near  $85^\circ N$  (dawn) at 23:25 and ends near  $85^\circ N$  (dusk) at 01:11. Orbit 2 (dot-dashed curves) begins near  $85^\circ S$  (dusk) at 03:44 and ends near  $85^\circ S$  (dawn) at 05:30 UT. Original data has been smoothed to avoid confusion of minor perturbations caused by occasional wobble in spacecraft attitude. Infrequent gaps in data are caused by drop out, noise, or other artificial effects.

term variations in the individual ion concentrations at a given latitude are also evident. In Figure 3 at low latitudes in both the dawn and dusk regions the difference in altitude between orbits 1 and 2 is rather small, yet significant changes in relative and individual concentrations are observed.

### High Latitude Ion Troughs

The pronounced high latitude depletion or trough in  $n(\text{H}^+)$  and  $n(\text{He}^+)$  is observed persistently, near  $60^\circ$  ( $L = 4$ ) in both the northern and southern hemisphere. In the northern hemisphere, the  $\text{H}^+$  trough, the first significant poleward minimum in  $n(\text{H}^+)$ , typically decreases to concentrations of  $n(\text{H}^+) = 1 - 2 \times 10^2$  ions/cm<sup>3</sup> during periods of low magnetic activity ( $K_p \leq 1$ ). Near dusk, the  $\text{H}^+$  trough generally occurs at higher latitudes, corresponding to  $L = 5 - 6$ , while on the dawn side the trough is observed nearer  $L = 4$ . Under disturbed conditions, ( $K_p = 3-5$ ), the  $n(\text{H}^+)$  trough level typically decreases to  $7 - 8 \times 10^1$  ions/cm<sup>3</sup>, and frequently moves several degrees lower in latitude. This effect is apparent in spite of such short term orbit to orbit variations seen in Figures 2 and 3, although it is not thoroughly established by our limited data sample.

In the southern hemisphere the  $\text{H}^+$  trough is somewhat less pronounced, particularly on the dawn side, and the trough minima typically decrease to concentrations near  $5 \times 10^2$  ions/cm<sup>3</sup>. The  $\text{H}^+$  trough is always accompanied by a nearly simultaneous trough in  $n(\text{He}^+)$ . The  $\text{He}^+$

trough generally exhibits the same characteristics as those of  $H^+$  although the  $He^+$  trough is sometimes steeper and more pronounced, particularly in the northern hemisphere.

In the northern hemisphere, the light ion trough is usually accompanied by a similar though much less pronounced depletion of  $n(O^+)$  and  $n(N^+)$ . In contrast, this heavy ion trough is seldom observed in the southern hemisphere and when seen is most prominent during enhanced magnetic activity ( $K_p = 3 - 4$ ).

#### Poleward Peak

The pronounced poleward enhancement or peak in the ion concentrations is another significant feature of the latitudinal variation. The poleward peak is defined as the maximum component of the fine structure consistently observed poleward of the light ion trough position. This enhancement, often observed nearly simultaneously throughout the composition, is typically most prominent in the major ions  $O^+$  and  $H^+$ . The peak is most pronounced in the northern hemisphere, where the resultant total ion density,  $N_i$ , increases to about  $10^4$  ions/cm<sup>3</sup> near 1000 kilometers. It is significant that a prominent peak is observed frequently but not persistently, and that the position of the peak is distributed over a fairly wide latitude range, 74 to 80° N and 77 to 87° S. In addition, a single, prominent peak is not always formed and occasionally several individual enhancements of as much as a factor of 3 in  $N_i$  occur within a spacing of several degrees of latitude. While no precise

pattern is evident in the longitudinal distribution of the peak, the frequency of occurrence and relative intensity of the enhancement definitely favor the northern dusk region.

### Combined Altitude and Latitude Variations

Prior to discussing the latitudinal variation of the composition more fully, it is desirable to identify and eliminate the effects of the altitude variation. Basically the altitude variations result from the fact that production, loss, and transport of ionization vary with altitude, which for an arbitrary ion  $X^+$  is expressed by

$$\frac{\partial n}{\partial t}(X^+) = q(X^+) - L(X^+) - \text{div}[F(X^+)], \quad (1)$$

where  $q$  is the production rate,  $L$  is the chemical loss rate and  $\text{div}[F(X^+)]$  is the gain or loss resulting from mass transport. The steady-state solutions to (1) determine altitude regimes where the ion distribution is governed either by chemical or diffusive equilibrium. In chemical equilibrium  $q = L$  and  $n(X^+)$  is determined by the local chemistry of formation and loss. In diffusive equilibrium mass transport dominates and production and loss are neglected. In order to eliminate the altitude variations we have attempted to identify approximate altitude regimes where chemical and diffusive equilibrium prevail and to subsequently apply appropriate expressions for translating the original data to a constant 1000 kilometers altitude. Before discussing the 1000 kilometer results, it is useful to examine the distributions of Figures 2 and 3 for appropriate supporting evidence. Because of the simultaneous variables

involved, this examination for equilibrium is only qualitative and applies primarily to the low and mid-latitude regions only, since other effects are believed to dominate at high latitudes.

In the case of  $O^+$ , it is generally believed that above the  $F_2$  peak near 300 kilometers diffusive equilibrium prevails. From this assumption the altitude distribution of  $O^+$  as a dominant ion is given by [cf. Mange, 1960]

$$n(O^+) \propto \exp [-Z'/H(8)], \quad (2)$$

where  $H(8)$  is the scale height with an effective mass of 8 AMU and  $z'$  is the geopotential altitude. Thus, throughout the altitude range of the orbit,  $O^+$  should be expected to decrease with altitude. Aside from the obvious influence of high latitude effects and occasional evidence of short term fluctuations, both the dawn and dusk  $O^+$  distributions qualitatively support the assumption of diffusive equilibrium.

Like  $O^+$ ,  $N^+$  could be expected to be in diffusive equilibrium above 415 kilometers in a distribution given by

$$n(N^+) \propto \exp [-Z'/H(6)], \quad (3)$$

[Mange, 1960]. In this case  $n(N^+)$  would decrease with altitude throughout the orbit, much as  $n(O^+)$ . In general  $n(N^+)$  follows this pattern in the dusk region where  $n(O^+)/n(N^+)$  remains near 10/1 at all altitudes. In the dawn region, however, the  $N^+$  distribution departs dramatically from that

of  $O^+$  and at altitudes below about 600 kilometers  $n(N^+)$  generally increases with altitude. In addition, significant short term variations are seen in  $n(N^+)$  between orbits. The sharp decrease in  $n(N^+)$  below 600 kilometers indicates that  $N^+$  is no longer in diffusive equilibrium, in contrast to the higher altitude dusk distributions. According to Bauer [1966a] several processes may compete in the production of  $N^+$  below 600 kilometers and while it is likely that chemical processes such as the dissociative charge transfer reaction



are important in determining the distribution of  $n(N^+)$  in this altitude range, the dominant source for this region is not well established. Due to the uncertainty in the reasons for the behavior of  $N^+$  in the dawn region we have chosen to neglect  $N^+$  in translating the dawn data to 1000 kilometers. Clearly, the evaluation of the role of  $N^+$  as a topside constituent must await more complete observations.

Production of the light ion  $H^+$  is believed controlled by the reaction



which provides both source and loss [Hanson and Ortenburger, 1961]. It follows that the distribution of  $H^+$  in chemical equilibrium is given by

$$n(H^+) \propto \exp [Z'/H(7)], \quad (6)$$

which also gives the distribution of  $H^+$  is in diffusive equilibrium, whenever  $n(H^+) \ll n(O^+)$ . When  $H^+$  becomes the dominant ion, the diffusive equilibrium distribution is given by

$$n(H^+) \propto \exp[-Z'/H(1/2)], \quad (7)$$

[Bauer, 1966b]. Thus at low altitudes, where  $O^+$  dominates,  $H^+$  is expected to increase rather rapidly with altitude, and this is generally observed, below about 600 kilometers in the dawn data. At higher altitudes  $O^+$  subsides,  $H^+$  becomes the dominant ion, and would be expected to decrease very slowly with altitude. This is observed in the dusk region at low and mid-latitudes, where  $H^+$  is the dominant ion, and the distributions of  $H^+$  reveal very little altitude variation.

Finally, the minor light ion  $He^+$  is produced by photoionization of He and is believed lost by reaction (4), which also serves as a source of  $N^+$  [Bauer, 1966a]. This results in

$$n(He^+) \propto \exp[Z'/H(24)], \quad (8)$$

for chemical equilibrium, and

$$n(He^+) \propto \exp[Z'/H(4)], \quad (9)$$

for diffusive equilibrium, when  $He^+$  is a minor ion, and

$$n(He^+) \propto \exp[-Z'/H(7/2)] \quad (10)$$



when  $n(\text{O}^+) \ll n(\text{He}^+) \ll n(\text{H}^+)$ . Thus  $\text{He}^+$ , like  $\text{H}^+$ , is expected to increase rapidly with altitude in chemical equilibrium, and in the northern dawn hemisphere this is observed. The  $n(\text{He}^+)$  distributions in the southern dawn region also tend to increase with altitude, although the behavior is more irregular. At higher altitudes  $n(\text{He}^+)$  would be expected to either gradually increase or decrease with altitude depending upon the ratio of  $n(\text{O}^+)$  to  $n(\text{He}^+)$ . In the dusk region the high altitude distributions of  $n(\text{He}^+)$  reveal limited altitude variation and evidence of diffusive equilibrium is not easily identified.

#### Translation of Results

The translation of the data consists of solving equations of motion under either chemical or diffusive equilibrium, using the original data as initial values, and subsequently moving either downward or upward from the original altitude to the 1000 kilometer level. We have assumed that  $T_i = T_e$  and have used a constant temperature of  $3000^\circ\text{K}$  for the dusk data and  $2100^\circ\text{K}$  for the dawn data. These temperatures were selected after averaging measured  $T_e$  distributions obtained near 1000 kilometers and at comparable local times from Explorer-22 [L.H. Brace, by private communication]. We have further assumed that above 600 kilometers  $\text{H}^+$  and  $\text{He}^+$  are in diffusive equilibrium and that  $\text{O}^+$  is in diffusive equilibrium throughout the orbit. In the dusk region  $\text{N}^+$  is assumed to be in diffusive equilibrium, and in the dawn region  $\text{N}^+$  is neglected. Below 600 kilometers we have assumed  $\text{H}^+$  and  $\text{He}^+$  to be in chemical equilibrium and have used equations (6) and (8) in extrapolating to 600 kilometers. Throughout

the range of diffusive equilibrium we have applied the formulation of Angerami and Thomas [1964] in performing the extrapolation.

With regard to the overall evidence for chemical and diffusive equilibrium, it is clear that the simultaneous variation of altitude and latitude, as well as the probable instability of the local time regions sampled, limits us to only qualitative conclusions. On the basis of this limited evidence we have chosen to use simple formulations of equilibrium in extrapolating to 1000 kilometers, and have deliberately avoided more complex assumptions involving equilibrium between the neutral gas, ion, and electron temperatures, temperature gradients along field lines, and upward and downward fluxes, any or all of which may well be significant. Thus, in neglecting the time and position dependent variables in the continuity equation, we have made a limited approach to an obviously complex problem. Nevertheless, we believe that the approximations used in the extrapolation account for the most obvious altitude effects, and thus permit a more meaningful evaluation of the latitudinal variation of the low and midlatitude composition. The pronounced features of the high latitude results, obtained at latitudes where equilibrium is least likely to prevail, are observed near 1000 kilometers and thus are in turn least affected by the extrapolation. Accordingly, the 1000 kilometer results reflect many features which are clear from an inspection of the original data.

Before examining the results of the extrapolation, it is important to note the relative geometry of the OGO-2 orbit, the 1000 kilometer level, and the dipole field. Referring to Figure 4, it is clear that in the low

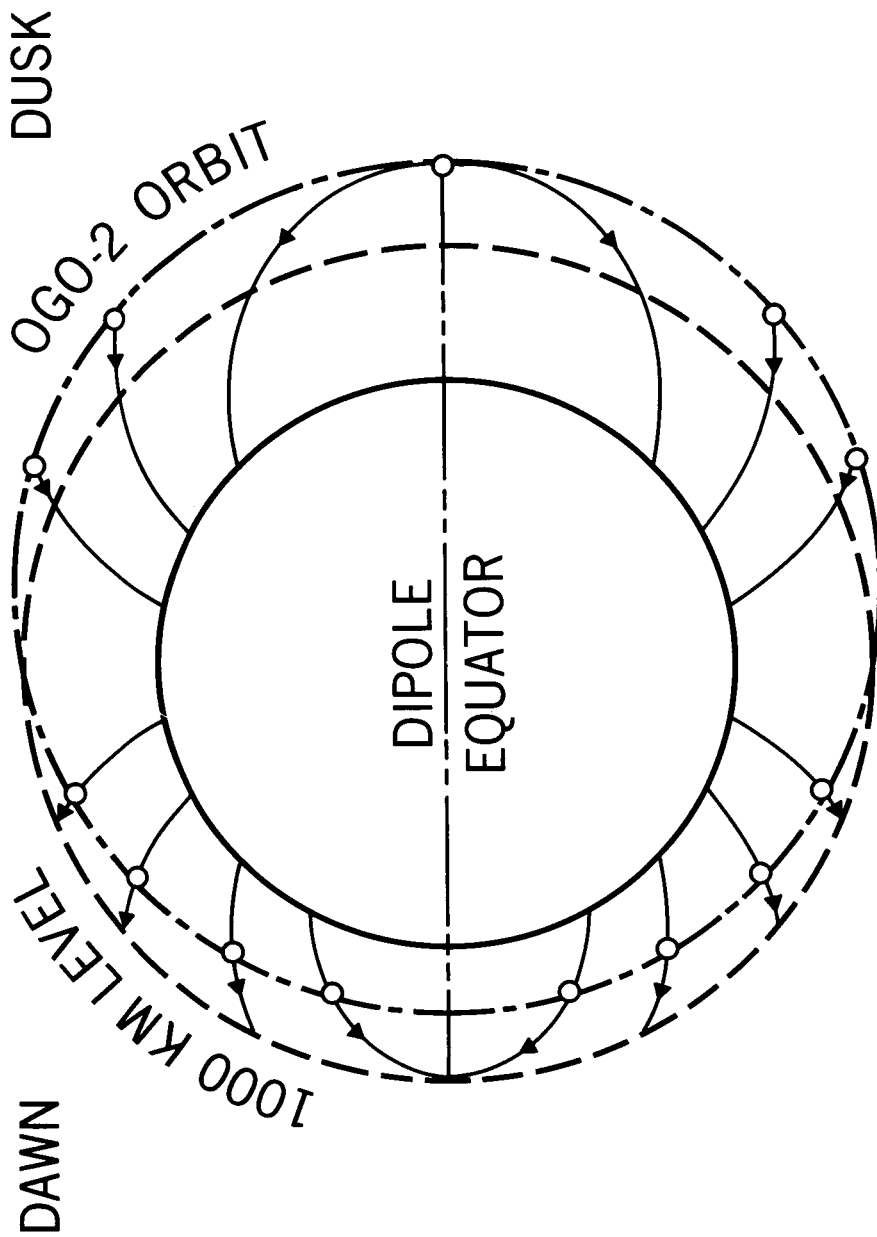


Figure 4. Schematic geometry of dipole field line extrapolation of data from OGO-2 orbit to 1000 kilometer level. Earth is viewed from the position of the sun, near the dipole equator. Note that in the dusk meridian the equatorial portion of the 1000 kilometer orbit cannot be filled in, and data points (circles) move along field lines to higher latitudes and are placed closer together. In the dawn meridian the data points move to lower latitudes, spread further apart, and the equatorial portion of the 1000 kilometer orbit is filled in.

latitude region of the dusk side of the orbit, the field lines intersecting the orbit cross the 1000 Km reference curve at higher relative latitudes. This effect is maximum near the equator and therefore the points on the orbit are extrapolated into two separate arcs on the 1000 Km reference level, leaving a gap about the equator. Additionally, the low latitude points on the 1000 Km level are more closely spaced than those near polar region. In the dawn half orbit the geometry produces an opposite result. In this case the field lines do not connect the equatorial portion of the orbit to the 1000 kilometer level. In addition, the original high latitude data are dispersed toward lower latitudes in the process of extrapolation.

#### Composition at 1000 Kilometers

The result of translating the ion distributions of Figure 2 to 1000 kilometers is given in Figure 5. It is clear that as expected the extrapolation has had little effect on the pronounced high latitude characteristics of the primary ions, although the concentrations are of course modified. The low and mid-latitude ion distributions however are significantly altered, and as expected the concentrations of the heavier ions are most affected. In the dusk region the low and mid-latitude distributions of  $O^+$  and  $N^+$  are noticeably increased, with the original equatorial depletions filling in considerably at 1000 kilometers. In the same region the character of the  $H^+$  and  $He^+$  distribution is essentially unchanged although the equatorial maximum in these ions is slightly emphasized. Accordingly, the observed pattern of  $O^+$  dominating at the poles and  $H^+$  prevailing at the equator is maintained at 1000 kilometers.

In the dawn region the distribution of each of the ions is extensively modified in moving to 1000 kilometers. In the case of  $n(O^+)$  the resultant distribution is considerably reduced in concentration and the latitudinal asymmetry is emphasized, with  $n(O^+)$  increasing from about  $2 \times 10^2$  ions/cm<sup>3</sup> near 50 degrees N to about  $3 \times 10^3$  ions/cm<sup>3</sup> near 50 degrees S. In the same region the distributions of  $n(H^+)$  and  $n(He^+)$  are also significantly changed in that the low altitude equatorial depletions in these ions are removed by the extrapolation to 1000 kilometers.

#### Mean Ion Mass and Total Concentration

The results of Figure 5 are combined to determine the mean ion mass,  $M_i$ , and total ion density,  $N_i$ , at 1000 kilometers, which are given in Figures 6 and 7 respectively. The mean ion mass approaches 14 - 16 AMU in both the northern and southern polar regions, and decreases rapidly near 50 degrees, falling to about 4 AMU near the equator. In both the dawn and dusk regions a distinct latitudinal asymmetry is observed, with  $M_i$  increasing more rapidly toward southern latitudes. In the dusk region the transition level, where  $n(H^+) = n(O^+)$  occurs at about 50 degrees in the northern hemisphere, and about 40 degrees in the south.

The total ion concentration at 1000 kilometers exhibits significantly different distributions in the dawn and dusk meridians. Near dusk  $N_i$  shows a trend toward an equatorial maximum near  $10^4$  ions/cm<sup>3</sup>, modified by a latitudinal asymmetry which favors the southern hemisphere. The poleward enhancements in  $H^+$  and  $O^+$  results in similar enhancements in  $N_i$  which reach about  $7 \times 10^3$  ions/cm<sup>3</sup> at 80 degrees north

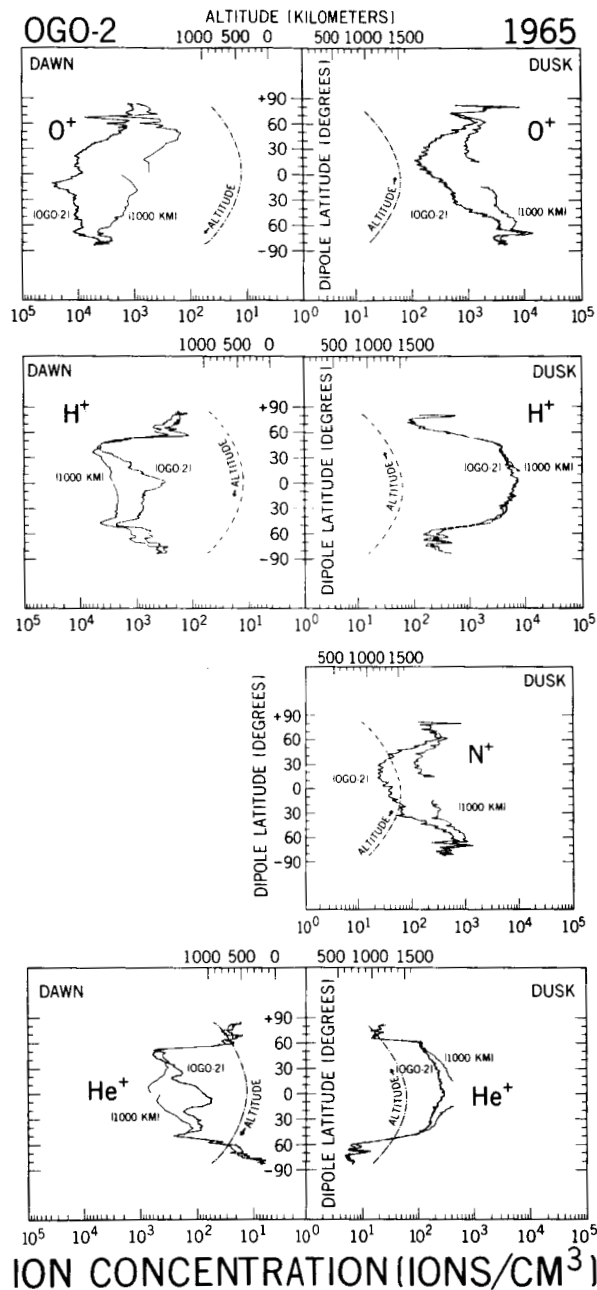


Figure 5. Comparison of distributions of  $O^+$ ,  $H^+$ ,  $N^+$  and  $He^+$  observed (Figure 2) at varying altitudes in OGO-2 orbit (circles) with result of extrapolating these data to a constant 1000 kilometer level (solid curves) using field aligned chemical and diffusive equilibrium theory. Gap near dusk equator in 1000 kilometer ion distributions results from field line-orbit geometry described in Figure 4. Discontinuities in 1000 kilometer ion distributions near dawn equator result from north-south asymmetry in original data. Only the dusk side  $N^+$  data is shown since the dawn  $N^+$  data are not extrapolated to 1000 kilometers. Initial data is the same as that shown in Figure 2 and covers the period 01:11 to 02:56 on 15 October 1965.

OGO-2

1965

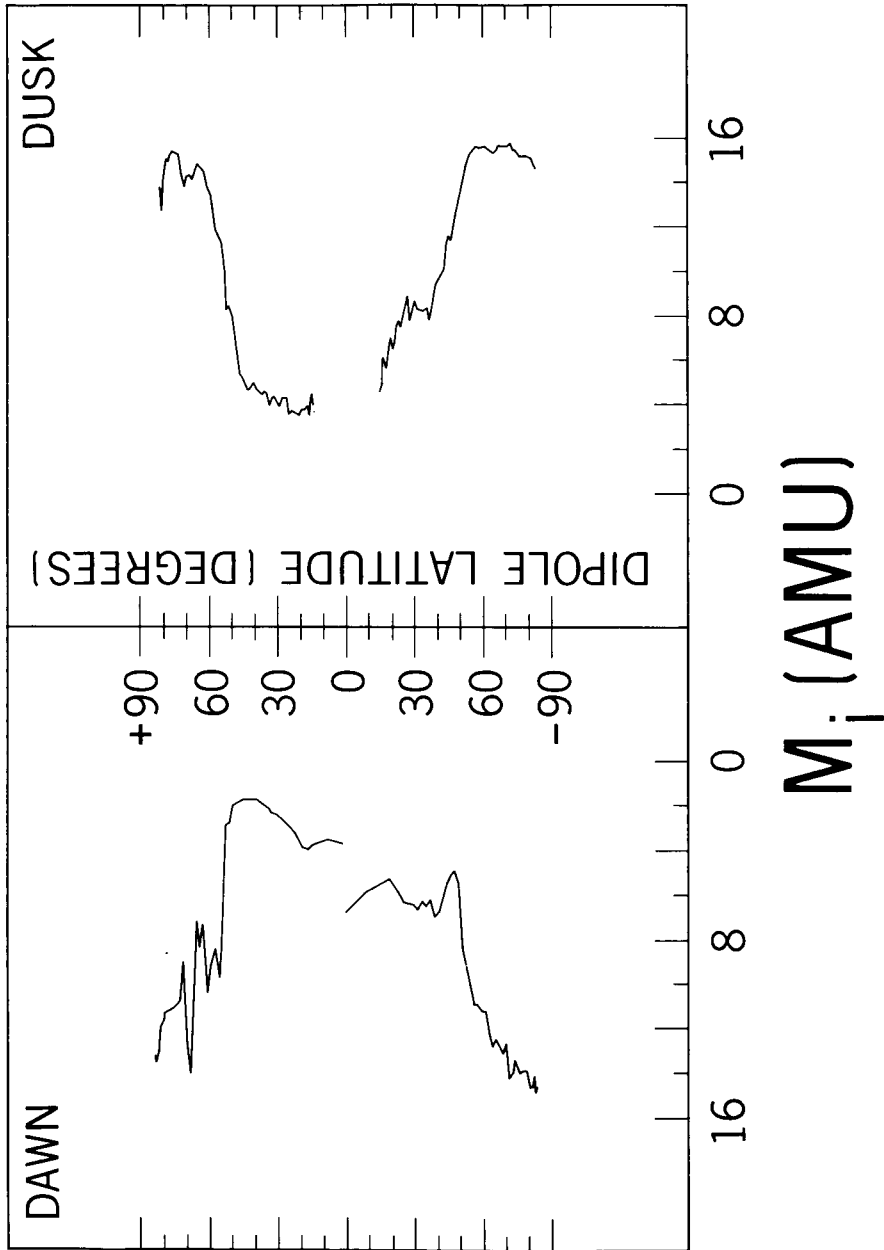


Figure 6. The mean ion mass,  $M_j$ , at 1000 kilometers, as a function of dipole latitude. Like  $N_j$ ,  $M_j$  is derived from the results of Figure 5, and includes the contribution of  $N^+$  on the dusk side only. The discontinuity near the dawn equator results from the strong latitudinal asymmetry in  $n(O^+)$  at 1000 kilometers.

OGO-2

1965

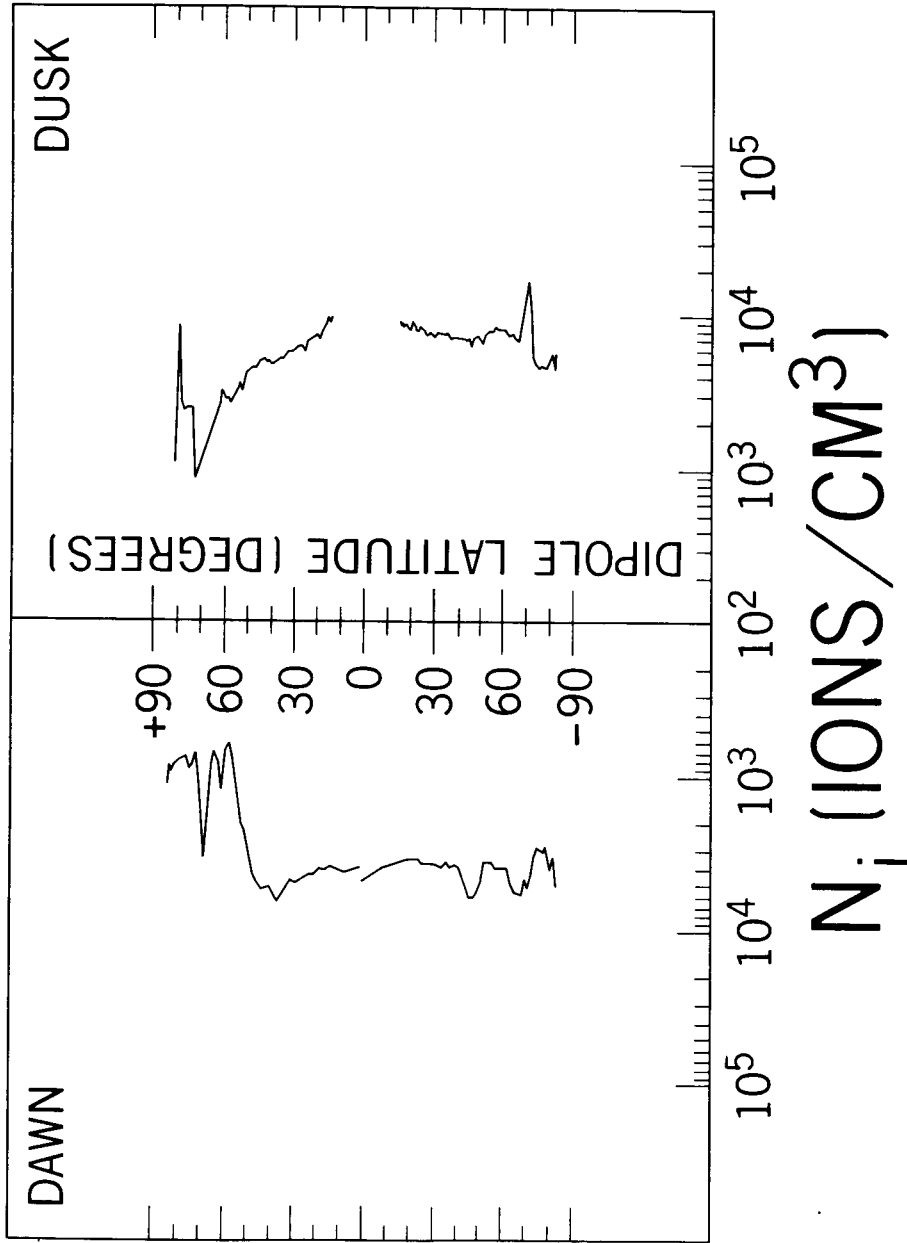


Figure 7. The total ion concentration,  $N_i$ , at 1000 kilometers, as a function of dipole latitude.  $N_i$  is derived as the sum of the concentrations of  $O^+$ ,  $H^+$ ,  $N^+$  and  $He^+$  at 1000 kilometers. These results are derived from the data of Figure 5. In the dusk meridian  $N_i$  includes the contribution of  $N^+$ , while in the dawn meridian  $N^+$  is neglected.



and about  $1.6 \times 10^4$  ions/cm<sup>3</sup> at 70 degrees south. The total concentration also exhibits a high latitude trough which falls to about  $6 \times 10^2$  ions/cm<sup>3</sup> near 70 degrees in the northern hemisphere.

In the dawn region the latitudinal variation in  $N_i$  is also asymmetric, exhibiting relatively increased concentrations at high southern latitudes. Superimposed on this trend is a relative depletion at low latitudes associated with a comparative enhancement in  $N_i$  toward higher latitudes, resulting in maxima near 40 degrees N and 45 degrees S. A high latitude trough occurs near 60 degrees N, where  $N_i$  decreases to about  $6 \times 10^2$  ions/cm<sup>3</sup>, followed by a poleward enhancement near 70 degrees N, where  $N_i$  increases to about  $3 \times 10^3$  ions/cm<sup>3</sup>. It is emphasized that no trough in  $N_i$  is seen in the southern hemisphere.

## DISCUSSION AND INTERPRETATION

### Global Characteristics of the Composition

It is significant that throughout the altitude range of 415 to 1525 kilometers, and at all latitudes, the ionosphere is composed of four significant ions, O<sup>+</sup>, H<sup>+</sup>, N<sup>+</sup> and He<sup>+</sup>. Some previous results deduced from a variety of direct and indirect measurements lacked resolution sufficient to establish the presence of N<sup>+</sup>. Ion composition data obtained from Electron - 1 and Electron - 2 in early 1964 also show that N<sup>+</sup> is a substantial component of the topside ionosphere near solar minimum although the polar ionosphere was not investigated [Istomin, 1966]. Our results show that N<sup>+</sup> is particularly significant at high latitudes, and in the auroral and polar regions reaches concentration levels

which well exceed  $n(\text{He}^+)$  and often equal  $n(\text{H}^+)$ . In November 1965 an ion composition experiment on Explorer 31 also confirmed that  $\text{N}^+$  is a significant constituent, often exceeding  $\text{He}^+$  in concentration [Hoffman, 1967].

As predicted by Nicolet [1961] and Bauer [1966b],  $\text{He}^+$  is observed to play a minor role during this period of low solar activity, and the topside ionosphere rapidly changes from an  $\text{O}^+$  dominated region into the protonosphere. The predicted expansion and contraction of the helium layer is further substantiated by earlier measurements during higher solar activity which show significant concentrations of  $\text{He}^+$  near 1000 kilometers [Taylor et al., 1961], [Bourdeau et al., 1962], and [Bowen et al., 1964]. Very recent results from the OGO-4 ion spectrometer in October 1967 show that a very significant helium layer is again developing and that at mid-latitudes  $n(\text{He}^+)$  frequently approaches the level of  $n(\text{H}^+)$ , near 1000 kilometers. Overall, these results reveal that  $n(\text{He}^+)$  is quite sensitive to changes in solar activity and suggest that a prominent helium ion belt will continue to develop during the latter part of this decade.

A third significant feature of the global distribution of the composition is the persistent pattern of the dominance of light ions at the equator and heavy ions at the poles. This result is consistent with estimates of the distribution of  $n(\text{O}^+)/n(\text{H}^+)$  deduced from Alouette-1 topside sounder results [Barrington et al., 1965], [Thomas et al., 1966], ion whistler results [Shawhan and Gurnett, 1966], and direct measurements aboard Ariel [Bowen et al., 1964] and Explorer 22 [Mayr et al., 1967].

Significantly, a companion ion trap experiment aboard OGO-2 has simultaneously observed approximate values for  $M_i$  which appear to be in good agreement with these data [Donley, 1967]. More recent evidence of the latitudinal variation in mean ion mass obtained from ion spectrometers aboard Explorer 31 [Hoffman, 1967] and OGO-4 also indicate general agreement with these results.

At latitudes below the positions of the ion troughs, the broad features of the composition appear to be consistent with the theory of Mayr et al., [1967] who suggest that at low and mid-latitudes, within the region of diffusive equilibrium, the latitudinal variation of the ion composition results from the latitudinal variation in electron temperature. Briefly, it is shown that the local cooling of electrons to hydrogen ions is most efficient at low latitudes where  $H^+$  and  $H$  are most abundant. This latitudinal variation in local cooling results in a latitudinal gradient in  $T_e$  and an associated relative inflation in the heavy ion scale height toward higher latitudes.

Superimposed on the broad latitudinal variation is a seasonal asymmetry, in which the latitudinal distributions of  $n(O^+)$  and  $n(N^+)$  significantly increase toward the southern summer hemisphere. It is likely that this asymmetry results from increased seasonal heating of the lower atmosphere. The increased heating produces an attendant seasonal inflation in the atmospheric scale height, an effect which is most prominent in the  $O^+$  and  $N^+$  distributions. As a further result the dawn and dusk distributions of  $M_i$  increase toward southern latitudes and the  $O^+$  to

$H^+$  transition level is displaced from about 50 degrees N to about 40 degrees S. This observed seasonal variation in  $M_i$  and  $N_i$  is generally consistent with results at 1000 kilometers obtained from Alouette-1 [Thomas et al., 1966] and Explorer 22 [Brace et al., 1967]. Chandra and Rangaswamy [1967] have shown that ionization at 1000 kilometers is strongly influenced by solar zenith angle and magnetic dip angle, and predict asymmetric  $N_e$  distributions which are similar to the seasonal asymmetry exhibited in both the  $N_e$  distributions observed by Brace et al. [1967] and in our  $N_i$  results.

#### High Latitude Ion Troughs

The dramatic depletion of the light ion concentrations above about 60 degrees followed by intense variability in the poleward distributions of the ion concentrations are persistent features of the dawn-dusk high latitude composition. These pronounced characteristics set the polar ionosphere apart as a region disturbed by significant energetic processes.

The northern hemisphere trough in  $N_i$  which is frequently observed near 60 degrees in our data appears to be the same phenomenon reported by Muldrew [1965] as the F-region 'main trough' in  $N_e$ . Similar trough-like structure in the topside  $N_e$  distribution has been reported by Sharp [1966], Thomas et al. [1966], Brace et al. [1967] and Donley [1967]. It is important to note that the  $N_e$  trough, like the  $N_i$  trough, has been observed to be most pronounced in the northern winter hemisphere, and as suggested by Sharp [1966], and Thomas et al. [1966] appears to be 'filled in' by enhanced ionization in the sunlit hemisphere.

It is significant that the trough in  $N_i$  results primarily from the depletion in  $n(O^+)$ , since  $O^+$  dominates at trough latitudes. This explains why in the warmer hemisphere, where  $n(O^+)$  is enhanced, the  $N_i$  trough is infrequently observed. In contrast, the troughs in  $n(H^+)$  and  $n(He^+)$  are observed persistently in both the northern and southern hemispheres. Thus, it is believed that the  $(H^+, He^+)$  trough, rather than the  $N_i$  (or  $N_e$ ) trough, is a permanent feature of the high latitude topside ionosphere.

#### Depletion of $H^+$ and $He^+$

A mechanism which may be responsible for the formation of the light ion trough was described by Dessler and Michel [1966] who proposed that the high latitude ionosphere would be depleted by the evaporation of plasma along field lines swept back toward the tail of the magnetosphere by the solar wind. It is significant that Dessler predicted that the critical flux of neutral hydrogen from below would limit the concentration of  $H^+$  in the topside polar ionosphere to about  $10^2$  ions/cm<sup>3</sup>, very nearly the typical 'background level' of  $n(H^+)$  we observe at the trough minimum and further poleward. The slight enhancement of the  $n(H^+)$  southern polar level relative to the northern level possibly results from increased ionization in the warmer hemisphere. The fact that the trough in  $n(O^+)$  and thus  $N_i$  is not as deep as that in  $n(H^+)$  follows from the fact that the heavier ion does not readily escape, and in the sunlit hemisphere increased production of  $O^+$  apparently balances the average depletion. The northern trough in  $n(O^+)$  possibly results from a combination of an upward flux and a loss through the charge transfer reaction (Equation 5) as  $H^+$  is depleted.

It has been assumed that the main trough in  $N_e$  may be related to the phenomenon of the whistler 'knee' or plasmopause observed near  $L = 4$ . As our data show however, the position, depth, and structure of the  $H^+$  trough and the  $O^+$  trough often differ significantly and thus comparisons of the  $L$  coordinates of the  $N_i$ , and presumably, the  $N_e$  trough with the position of the plasmopause may not be rigorous. The light ion distributions are much more sensitive to the thermal plasma depletion mechanism and provide resolution necessary for a more meaningful correlation. Significantly, a comparison of several examples of the latitude at which ground-to-satellite (OGO-2) VLF Transmissions are abruptly reduced [Heyborne, 1966] and the latitude at which we observe the  $H^+$  and  $He^+$  troughs agree rather well. Similarly, the comparison of several light ion trough latitudes and the position of the atmospheric whistler cutoff detected from OGO-2 agree very well [D.L. Carpenter, by private communication]. These observations are in turn closely related to the recent results of Carpenter et al. [1968] who have identified a close spatial relation between the whistler cutoff and the 'knee' position.

The plasma escape mechanism has been considered further in a model of the magnetospheric plasma distribution recently developed by Nishida [1966]. This model predicts the draining of high latitude field tubes resulting from the flow of light ions into the tail region and further suggests that the plasmopause, or boundary of field lines from which plasma escape is prevented, should exhibit a distinct dawn-dusk asymmetry. This predicted asymmetry follows the early observations of

Carpenter [1966] that the plasmopause is extended outward in the dusk meridian as shown in Figure 8. A similar asymmetry is apparent in the direct measurements of the plasmopause obtained from OGO-1 [Brinton et al., 1968] and OGO-3 [Taylor et al., 1968]. The observed asymmetry in the dawn-dusk latitudes of the  $H^+$  trough, in which the dusk ion trough often appears at higher latitudes and L coordinates, appears to be consistent with the whistler plasmopause asymmetry. The fact that the trough asymmetry is more noticeable in the L coordinate is consistent with the proposed magnetospheric link between the plasmopause and the light ion trough. Similarly, the evidence that the light ion trough deepens with increasing  $K_p$  agrees with the observation that the plasmopause moves to lower L positions during enhanced magnetic activity [Carpenter, 1966], [Taylor et al., 1968], [Binsack, 1967]. As suggested by Dessler [1959] it is likely that increased high latitude ionospheric heating is associated with increased magnetic activity. Such increased heating coupled with increased distortion of the magnetic field lines could well produce the observed deepening in the ion troughs.

#### Poleward Ion Peak

Poleward of the light ion trough the composition is seen to be constantly fluctuating, which agrees with the evidence of polar ionosphere fluctuations observed by Thomas et al. [1966], Brace [by private communication], and Donley [1967]. The instability we observe in the most prominent feature of this region, the polar peak, is indicative of the variability of the ionosphere at very high latitudes. It is significant that while the peak is not observed persistently, it does occur in both

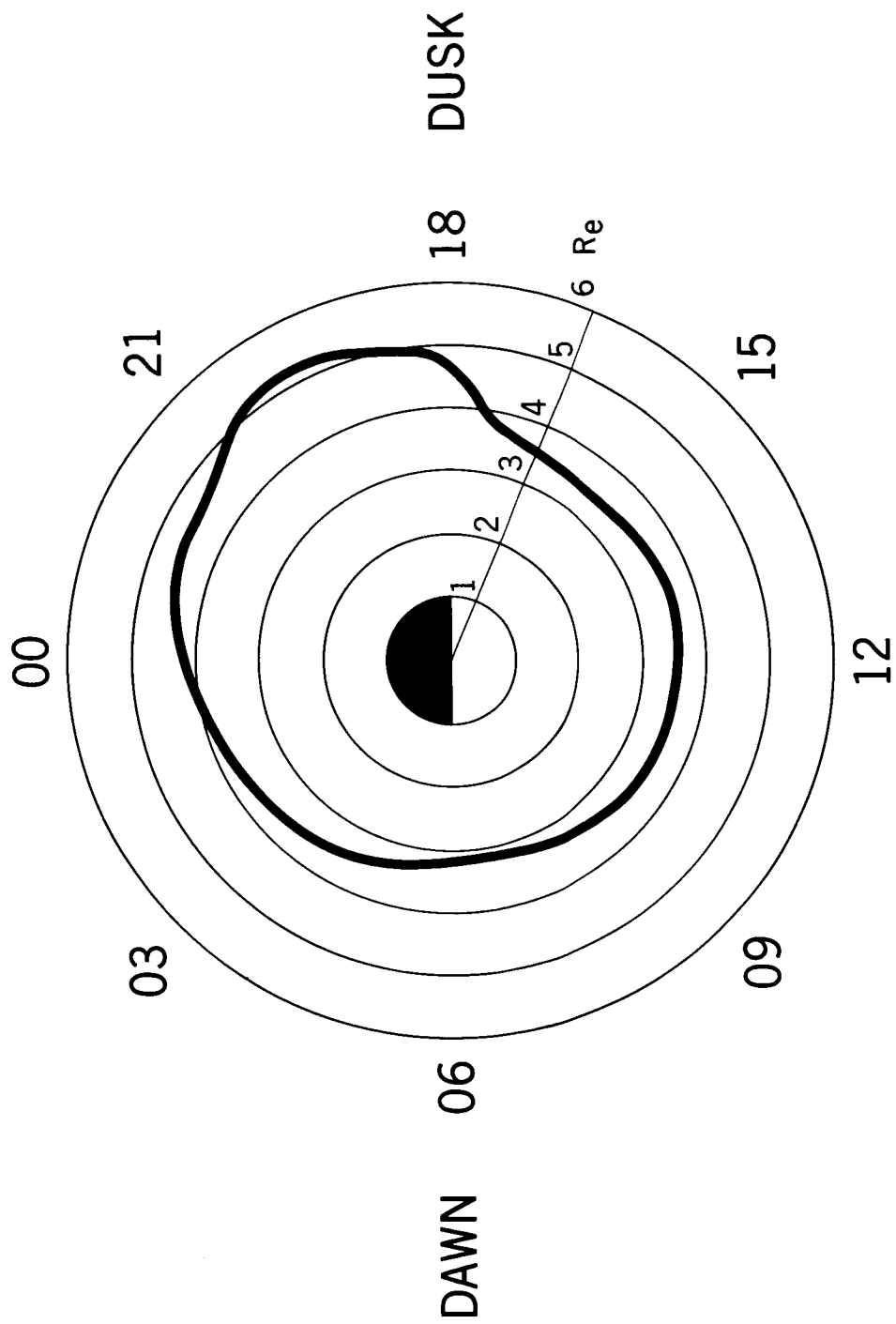


Figure 8. Average equatorial radius of the plasmapause or whistler knee versus local time during periods of moderate geomagnetic activity, in July and August 1963. Concentric circles indicate distance increments of 1  $R_e$ . [after Carpenter, 1966].



hemispheres, although the northern peak is usually most pronounced. It is observed that while  $n(O^+)$  usually dominates, the peak often reflects very similar enhancements in each of the ions. Similar polar peaks in  $N_e$  have been reported by Thomas et al. [1966] near  $78^\circ$  N invariant at 1000 kilometers in winter afternoon. Donley [1967] observes an ionization peak near  $80^\circ$  N invariant at 2500 kilometers in winter morning, and in addition with the OGO-2 ion trap experiment observes similar peaks in  $N_i$  which are simultaneous with our data [ J.L Donley, by private communication ]. Both Thomas and Donley have observed the polar peak to be most prominent near noon, and suggest that the enhancement arises from increased ionization at lower levels, produced by precipitation of energetic particles along neutral lines in the distorted magnetosphere. This view is consistent with that of Oguti and Marubashi [1966] and of Nishida [1967] who in addition shows, from Alouette-1 data, that the polar peak is broad, with an appreciable lateral component extending to 18:00 hours LT near  $77^\circ$  N dipole. An alternate mechanism appears to exist in the theory of Dessler and Michel [1966] who suggest that the escape of high latitude plasma will be balanced by a solar wind flux returning from the tail of the magnetosphere. Clearly, if the light ion trough is explained by plasma escape along open field lines, field lines at still higher latitudes near the polar peak would be swept back to the tail and thus be capable of returning energetic plasma from that region. Whether the  $N_i$  peaks we observe are components of the rather permanent solar wind induced ionization peak described by Nishida or are the result of transient anomalies of the polar ionosphere is unclear. The variability

of the definition and amplitude of peaks observed in the northern and southern hemispheres however seems to suggest that nonstatic mechanisms, varying with solar activity and aligned with the magnetic field are responsible for the peak and associated fine structure.

### Exosphere - Plasmasphere Coupling

The northern hemisphere portions of the dawn and dusk ion distributions of Figure 6 have been extrapolated beyond 1000 kilometers to obtain the equatorial  $N_i$  profile shown in Figure 9. Beyond about  $1.25 R_e$  the heavier ions have decreased to less than 10%  $N_i$  and  $N_i$  becomes essentially  $n(H^+)$ . In Figure 9 we have included for a most important comparison a magnetospheric  $N_i$  profile obtained from the OGO-3 ion composition experiment. This profile, which was obtained near dusk in the northern summer hemisphere, is rather typical of the OGO-3 data which frequently identify the plasmopause as an abrupt boundary where  $n(H^+)$  decreases by as much as an order of magnitude in 250 kilometers or  $0.1 L$  [Taylor et al., 1968]. Comparison of several simultaneous knee whistler and ion plasmopause measurements obtained on OGO-3 show good agreement [D.L. Carpenter, by private communication].

The pronounced departure between the equatorial  $N_i$  distributions above about  $5.2 R_e$  (Figure 9) is a very significant feature of our results. Based on the earlier discussion, it might be expected that the equatorward boundary of the  $H^+$  trough, in diffusing upward along closed field lines to high altitudes, would form the abrupt plasmopause. Clearly, however, even the steep  $H^+$  troughs which we observe cannot, through simple

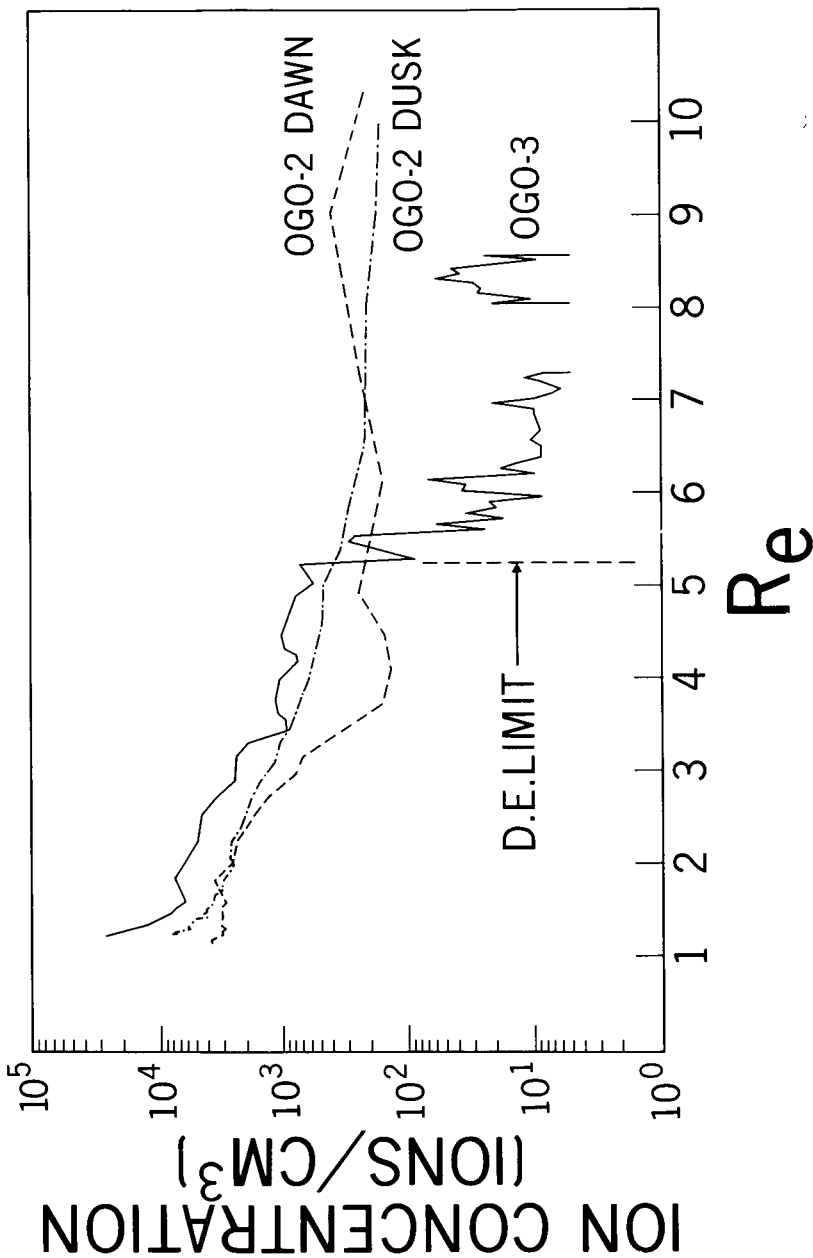


Figure 9. Equatorial profiles of total ion concentration  $N_i$  versus geocentric earth radius  $R_e$ . The OGO-2 ion distributions were obtained by extrapolating the northern hemisphere portions of the data of Figure 6 further, to the dipole equator. The OGO-3 profile was obtained by extrapolating to the equator a northern hemisphere  $n(H^+)$  profile observed between 3000 and 30,000 kilometers on 17 July 1966. Because of the low inclination OGO-3 orbit, the extrapolation had negligible effect on the initial profile. The OGO-3 profile does not drop below  $5 \times 10^6$  ions/cm<sup>3</sup>, the limiting sensitivity. Note that the light ion troughs which were observed near  $57^\circ N$  ( $L = 3.7$ ) (dawn) and  $65^\circ N$  ( $L = 4.7$ ) (dusk) at the 1000 kilometer level do not result in similar sharp gradients in the equatorial extrapolations of these data. Similarly, the rapid decrease observed near 5.2 L in the OGO-3 profile does not reflect the upward diffusion of the light ion trough but rather appears to mark the high latitude limit of diffusive equilibrium (D.E.,).

field aligned diffusion, produce such sharp gradients as that observed near  $5.2 R_e$  in the OGO-3 data. Accordingly, if the ions which populate the magnetosphere are constrained to diffuse along the magnetic field lines, our results, like those of Carpenter [1966] indicate that within the plasmasphere diffusive equilibrium prevails, while at the plasma-pause and beyond the plasma distribution is governed by some significantly different process.

The combined evidence of (1) the dramatic depletion of light ions at high latitudes, (2) the persistent variability of the polar ionosphere, (3) the apparent correlation between the whistler cutoff, the  $H^+$  trough, and the plasmopause, and (4) the breakdown of diffusive equilibrium at the plasmopause leads to the conclusion that the exospheric plasma is divided into two distinct regions: the plasmasphere and the polar magnetosphere.

At low and mid-latitudes, below about 60 degrees, the topside ionosphere contains only two significant light ions,  $H^+$  and  $He^+$ . The relative abundance of  $H^+$  and  $He^+$  are largely determined by the phase of the solar cycle, with  $H^+$  dominating at low activity. This mixture serves as the source of thermal ions which through diffusion populate the plasmasphere. As defined by Carpenter [1966] and extended by Nishida [1966] the plasmasphere is seen as an envelope of cool co-rotating plasma. The composition data indicate that the poleward boundaries of the plasmasphere are defined by the light ion troughs. The lightest ion,  $H^+$ , will

diffuse upward most readily and thus above 1000 kilometers, the plasmasphere rapidly becomes an  $H^+$  dominated region, or the protonosphere. It is apparent that the concentration of  $He^+$  is quite sensitive to solar activity and it is expected that toward solar maximum an appreciable helium ion layer will form at high altitudes. At the same time it would be expected that under increased solar wind pressure the plasmasphere boundary would be compressed inward. Under these combined circumstances the diffusion of  $H^+$  to great distances should be decreased and the plasmopause would be observed at lower L positions.

Indeed the whistler results indicate that the plasmopause was generally located much nearer the earth during solar maximum than near minimum. Near solar maximum Corcuff and Delaroche [1964] report plasmopause positions as close to the earth as  $L = 2$ , while nearer solar minimum the plasmopause has been observed typically near  $L = 4$  [Carpenter, 1966]. Conversely, there is tentative evidence from the comparison of earlier whistler data with more recent spectrometer data that the plasmasphere boundary has moved further from the earth during low solar activity, to positions typically near 5-6L [Taylor et al., 1968]. Similarly, the evidence of the breathing of the helium layer is consistent with this pattern and may explain why during higher solar activity equatorial ionization profiles such as those deduced from Ariel-1 topside composition data [Thomas and Dufour, 1965] fall off more rapidly with distance than do our results.

The overall picture of the exospheric ion composition suggested by our measurements is of course an incomplete and preliminary result. Clearly, significantly more data are required to establish the complete latitudinal as well as diurnal and seasonal variation of the composition of the topside ionosphere. Nevertheless, these results demonstrate that the exosphere is not a simple, spherical envelope, and suggest a strong coupling between the inner and outer ionosphere. The balance between such possibly competing solar cycle effects as the increased production at low altitudes, which would tend to expand the plasmasphere, and the attendant increased solar wind pressure, which would tend to compress the plasmasphere, must be examined much more completely. Furthermore, a more concentrated effort must be made to correlate measurements in the outer plasmasphere with observations of the composition at high latitudes, to better define mechanisms by which these dynamic regions may be coupled.

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