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OBSERVATIONS OF HYDROGEN AND HELIUM IONS DURING A PERIOD OF RISING SOLAR ACTIVITY

H. A. TAYLOR, JR.
H. G. MAYR
H. C. BRINTON

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by

H. A. Taylor, Jr., H. G. Mayr, and H. C. Brinton

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Laboratory for Atmospheric and Biological Sciences
Goddard Space Flight Center
Greenbelt, Maryland

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H. A. Taylor, Jr., H. G. Mayr, and H. C. Brinton

ABSTRACT

Pronounced latitudinal variations have been revealed in the distributions of the primary ions of the upper ionosphere (O^+, H^+, He^+, and N^+) obtained from the OGO-2 and 4 satellites, during the period 1965-1968. These variations, which tend to dominate the distributions of n(H^+) and n(He^+), include (1) the high latitude light ion trough observed near 60° dipole latitude, L=4 (associated with the plasmapause), (2) a pronounced anomaly in n(He^+), in the form of a broad, deep trough located near the dipole equator, and (3) a seasonal prominence in n(He^+), which favors the winter hemisphere. In addition to the n(He^+) anomaly, which is reflected to a lesser extent in n(H^+), the ion composition exhibits throughout a considerable variability, with respect to the orientation of solar zenith angle and magnetic field inclination, which in some cases appears to completely replace the expected influence of altitude. At positions where α (defined as the angle between the earth-sun line and the dipole equator) reaches its maximum value (maximum seasonal asymmetry), the equatorial trough in n(He^+) extends over a region as broad as 40° dipole latitude, wherein n(He^+) decreases by a factor of 5 or more relative to midlatitude concentrations observed near ± 30°-40° dipole latitude. Superimposed with the equatorial trough, a broad winter hemisphere prominence, or bulge, is observed in the n(He^+) distributions, wherein the winter concentrations of He^+ exceed summer concentrations by as much as a factor of 4, at comparable mid and high latitudes.

For most values of α, the H^+ distributions exhibit a similar but much reduced equatorial trough, and an opposite behavior at winter high latitudes, where $n(H^+)$ generally decreases with increasing α. When α decreases toward minimum amplitude (minimum seasonal asymmetry), the equatorial troughs in $n(He^+)$ and $n(H^+)$ are greatly reduced, and the high latitude seasonal asymmetries in $n(He^+)$ and $n(H^+)$ also decrease. The observed 'wobble' in the light ion distributions produces situations wherein $n(H^+)/n(He^+)$ may change dramatically, between orbits. Values of $n(H^+)/n(He^+)$ varying between about 3 and 60 have been observed over a wide range of latitudes, longitudes, and local times in the altitude range of 600-900 km. Typically, $n(H^+)/n(He^+)$ is rather large (3-5 or greater) and He^+ becomes prominent only in narrow (10-15° latitude) regions in the high latitude winter ionosphere. Selecting on the basis of α, a comparison of H^+ and He^+ distributions obtained 1 year apart in December, 1967-68, reveals a striking similarity in the respective latitudinal distributions of the ions. Contrary to theoretical predictions, these data show little or no temporal change in $n(H^+)$ and $n(He^+)$. Thus, at these altitudes and positions, the data identify the absence of a prominent global He^+ belt during this period approaching the maximum of solar cycle 20. The extreme variability in the light ion distributions may, in part, result from such dynamic factors as (1) chemical and ionization processes related to latitudinal gradients in the neutral composition, such as that identified as the winter helium bulge, or (2) the large scale redistribution of ionization through neutral wind-ionosphere interaction. This variability is seen as a factor which significantly complicates the evaluation of previous comparisons of the behavior of the ion composition during a solar cycle, and indicates a need for improved techniques to be used in future studies.

OBSERVATIONS OF HYDROGEN AND HELIUM IONS

DURING A PERIOD OF RISING SOLAR ACTIVITY

INTRODUCTION

Since the first prediction by Nicolet [1961] of the importance of helium as a constituent of the upper atmosphere, considerable attention has been directed toward examining, by theory and measurement, both the short and long term behavior of He^+ relative to H^+, as components of the upper ionosphere. Ionospheric models proposed by Hanson [1962], Bates and Patterson [1962], Bauer [19[illegible]], Rush and Venkateswaran [1965], and others, generally agree in predicting that a significant He^+ belt should form as a result of increased temperatures associated with conditions of solar maximum, in contrast to the solar minimum period when the He^+ belt is predicted to shrink significantly.

During solar cycle 19 the frequency and correlation of both direct and indirect measurements of the He^+ and H^+ content near 1000 km was sufficiently limited that a conclusive evaluation of the model behavior of the light ion variation is most difficult if not impossible. Measurements obtained from ion traps and spectrometers during the latter half of solar cycle 19 [Bourdeau et al., 1962] [Hanson, 1962] [Taylor et al., 1963] indicate that at certain locations, near 1000 km and above, during elevated solar activity, conditions wherein $n(He^+/n(H^+) >1$ apparently did exist. Results of the Ariel-1 plasma probe [Bowen et al., 1964] obtained in 1962, nearer solar minimum, indicate the persistence of a dominant He^+ belt, extending to at least 1000 km. In 1964, during solar minimum, spectrometer measurements by Istomin [1966] and radar backscatter observations by Carlson and Gordon [1966] both indicated the dominance of $n(H^+)$ over

$n(He^+)$ near 1000 km. Additional measurements during the early part of solar cycle 20 by satellite borne spectrometers [Taylor et al., 1968] [Hoffman, 1967] [Brinton et al., 1969] and radar backscatter [Farley et al., 1967] [Carlson and Gordon, 1966] indicate that, for those locations sampled, He^+ was consistently a minor ion near 1000 km in the period 1965-66. In attempting to compare the above measurements, it must be recognized that wide differences exist, both in techniques employed and perhaps more importantly, in locations studied, due to significant variability in the local time, altitude, season, and longitude of the observations.

It is the purpose of this paper to present the most recent direct measurements of H^+ and He^+ distributions, which indicate that during 1967-68, in a period approaching the maximum of solar cycle 20, no significant He^+ belt has formed near 1000 km. Variability with respect to season and local magnetic time, which is observed throughout the ion composition, is particularly pronounced in $n(He^+)$ and $n(H^+)$, and is presented in detail. Some implications of this variability for the investigation of ionospheric response to solar changes, and for the development of new ionospheric models are discussed briefly, with comments on possible mechanisms which could be responsible for the observed anomalies.

The Experimental Equipment

The thermal positive ion composition experiment on the OGO-4 satellite is essentially identical in characteristics to the Bennett-rf spectrometers used on the OGO 1 and 2 satellites, and described elsewhere [Taylor et al., 1965; Brinton et al., 1968]. The salient characteristics of the experiment are the sensitivity: $10\text{-}5\times10^6$ ions/cm^3; resolution: 1 in 20 AMU; mass range: 1-45 AMU; and ion sampling rate: 25.6 seconds between consecutive ion samples, corresponding to a resolution of about 175 km along the orbit.

Location of Observations

The pertinent elements of the OGO-4 orbit are given in Figure 1. During August and December, 1967, when many of the illustrated observations were obtained, the orbit was inclined near 86° with a perigee of about 414 km and an apogee of about 913 km, located at about -55° geographic longitude, near the dusk meridian (1730 hours L.T.). The orbital period was approximately 100 minutes, so that consecutive dusk-side latitudinal ion profiles were obtained at geographic longitude intervals of approximately 24°. The illustrated data sample has been selected from a series of dusk-side half-orbits, so as to optimize data correlations under closely related conditions of altitude, latitude, longitude, local time, and season. Additional data sets obtained at non-selected, widely different local times (dawn, day, night) and seasons, although not shown, generally substantiate the salient features described in the dusk results.

RESULTS

Primary Ions

Throughout the altitude range of about 400 to 900 km, the primary positive ions observed in the upper ionosphere are O^+, H^+, N^+, and He^+. In Figure 2 an example is given of the latitudinal distributions of these primary ions, observed on August 6, 1967, in a dusk half-orbit, near 1739 L.T. The general characteristics of these results, including (1) the dominance of O^+ between 500 and 900 km during the day, (2) the presence of N^+ distributed in concentrations typically about 10% $n(O^+)$, (3) the secondary importance of He^+, where $n(H^+)/n(He^+)$ is typically 10 or higher, are quite similar to earlier direct measurement results reported by Taylor et al., [1968], Brinton et al., [1969], Hoffman [1967], and Istomin [1966].

High Latitude Ion Trough

The present measurements, however, reveal several striking characteristics not reported in the previous ion composition results. First, near 70°S dipole latitude, the 'light ion trough' [Taylor et al., 1968] observed in $n(H^+)$ and $n(He^+)$ is accompanied by a very pronounced trough in $n(O^+)$ and $n(N^+)$. The high latitude light ion trough in $n(H^+)$ and $n(He^+)$ has been observed repeatedly (near 60° dipole, L=4) in the ion composition results from OGO-2 and has been associated with the plasmapause and vlf-whistler cutoff [Taylor et al., 1969]. In the limited earlier results, however, the light ion trough was accompanied by a significant trough in $n(O^+)$ and $n(N^+)$ only during increased magnetic activity ($Kp > 3$). On August 6 the maximum Kp during the 6-hour period preceding the profile in Figure 2 was Kp = 2+. Also it is observed that with increasing latitude, above -30°S, $n(He^+)$ approaches $n(H^+)$ more closely and finally exceeds $n(H^+)$ in a very narrow latitude interval near 70°. In addition, it is noted that the high latitude light ion trough, which was observed to be prominent during October 1965 (OGO-2) in both the northern and southern hemispheres near 1000 km, is greatly reduced in the summer hemisphere portion of Figure 2. In this pass, the trough region is traversed below 600 km, which is a lower altitude range than that in which most of the OGO-2 light ion trough crossings were made.

Equatorial Trough in $n(He^+)$ and $n(H^+)$

A second feature of the data of Figure 2, which is most pertinent to the subject of this paper, is the pronounced equatorial trough in n(He^+), extending from about +30°N to -30°S, in which n(He^+) decreases by as much as a factor of 5, relative to the mid-latitude concentrations. Significantly, the n(He^+) trough occurs over a rather wide altitude range (700-900 km) and in an altitude region where n(He^+) would be expected to be increasing smoothly with increasing altitude as a minor ion in diffusive equilibrium Bauer [1966]. In the same altitude-latitude interval note that n(H^+) exhibits a similar, but significantly reduced equatorial trough in which n(H^+) decreases by at most a factor of 2 relative to the midlatitude concentrations. Simultaneously, the n(O^+) and n(N^+) profiles, which appear to be changing smoothly as a function of altitude, do not exhibit any detectable trough structure.

The equatorial trough in n(He^+) is observed to vary in both depth and latitudinal position, as the earth rotates beneath the OGO-4 orbit. In Figure 3, a series of n(He^+) profiles obtained near 1739 L.T. during the period August 1-7, 1967, are displayed as a function of geographic longitude and α (defined as the angle between the earth-sun line and the dipole equator). Although altitude variations of as much as 130 km occurred between corresponding dipole latitudes on different passes, the gross pattern of a pronounced variation in the character of the n(He^+) equatorial trough is quite apparent. The broadest and deepest troughs occur near -30° to -100° (American longitudes, maximum values of α) while at European and Asian longitudes (0° to +160°, minimum values of α) the trough is less pronounced. At +117° longitude the trough has almost disappeared.

Superimposed with the equatorial trough in n(He^+) is the evidence of a strong seasonal asymmetry or bulge in the distributions of n(He^+), wherein winter concentrations reach levels greater by as much as a factor of 4 relative to concentrations at the same latitude in the summer hemisphere. At longitudes where the equatorial trough is more pronounced, (large values of α) the seasonal asymmetry in $n(He^+)$ generally reaches larger values. Although the seasonal character of the asymmetry is not fully established by the data in Figure 3, due to the uncertainty of the significance of the summer-to-winter altitude variation, data presented later show that the asymmetry exists, <u>independent</u> of significant altitude variation, and is thus a seasonal shift.

The variability observed in $n(He^+)$ with respect to longitude suggests the strong control of the magnetic field in regulating the ion distributions. The general correlation between the maximum values of α, the breadth and depth of the equatorial trough, and the emphasis in the seasonal asymmetry is reasonably good, considering the spread in universal time and the altitude variations contained within the sample.

<u>Longitudinal Variability in $n(He^+)$ and $n(H^+)$</u>

In order to examine more quantitatively the contrast in $n(He^+)$ observed at different longitudes and α values, two $n(He^+)$ profiles, obtained at +117° long. ($\alpha = 5°$) and -55° long. ($\alpha = 29°$), are compared in Figure 4. The $n(H^+)$ distributions observed at the same locations are given in Figure 5.

In Figure 4 the pronounced variation in the depth and position of the equatorial helium ion trough is obvious. At +117° long. ($\alpha = 5°$) the trough has almost vanished. Although the altitude ranges of the two profiles in Figure 4 differ by as much as 95 km, it is not credible that the altitude difference accounts for the gross change in trough character. A second, distinct feature of the data in Figure 4 is the significant difference in $n(He^+)$ observed between hemispheres. At comparable latitudes $n(He^+)$ is typically higher by a factor of 3-4 in winter, relative to summer. For the higher value of α (29°) this asymmetry is further enhanced, with the mid latitude winter $n(He^+)$ peak moving further south and broadening significantly. Similar enhancements in $n(He^+)$ in the winter hemisphere are observed in the re n where $\alpha = 20°-30°$, i.e. where the solar-magnetic winter season is most pronounced.

In Figure 5 the $n(H^+)$ profiles exhibit considerably less variation with longitude and α, relative to the $n(He^+)$ profiles, although the variations in $n(H^+)$ are by no means insignificant. In general, the $n(H^+)$ profile at $\alpha = 29°$ suggests that the overall ion distribution has been 'tilted' toward the southern (winter) hemisphere. The moderate equatorial trough in $n(H^+)$ at $\alpha = 29°$ has, as in the case of $n(He^+)$ almost vanished at $\alpha = 5°$.

A further comparison of Figures 4 and 5 reveals considerable variability in $n(H^+)/n(He^+)$, with respect to both latitude and α. At the position $\alpha = 29°$, $n(H^+)/n(He^+)$ is about 20 near northern high latitudes (600 km), decreases to 50-60 at low latitudes (700-800 km), increases to 10 near southern mid latitudes (900 km) and finally approaches 1 or less in a very narrow latitude range near -70°. At the position $\alpha = 5°$ $n(H^+)/n(He^+)$ is about 25 near high northern latitudes (600 km), decreases to about 10 through mid and low latitudes (700-800 km) and then maintains a value of about 8-10 throughout high southern latitudes (800-900 km).

A final feature of the data of Figures 4 and 5 is the evidence of a seasonal asymmetry in the position and depth of the high latitude troughs in $n(He^+)$ and $n(H^+)$. Note that at $\alpha = 29°$ the depth and position of the high latitude trough in both hemispheres has changed appreciably, relative to the corresponding trough positions at $\alpha = 5°$. Near maximum solar-magnetic season for this date ($\alpha = 29°$) the high latitude trough in $n(H^+)$ drops to concentrations lower by as much as a factor of 4 relative to the trough level observed at minimum seasonal position (α = 5°). This apparent deepening of the $n(H^+)$ trough is apparently out of phase with the formation the winter bulge in $n(He^+)$.

It is important to note that the results of the OGO-2 icn composition experiment [Taylor et al., 1968] also reveal evidence of the equatorial He^+ anomaly in dawn-dusk $n(He^+)$ distributions obtained near solar minimum, in October, 1965. While the $n(He^+)$ distributions near 1500 km (dusk) show evidence of a less pronounced trough, equatorial depressions in $n(He^+)$ of as much as a factor of 2 have been observed. At dawn, pronounced and variable $n(He^+)$ troughs of as much as a factor of 5 were reported near the dipole equator, between 400-500 km, which is consistent with dawn $n(He^+)$ troughs observed in the OGO-4 data. A seasonal asymmetry in $n(He^+)$ favoring the winter (October) hemisphere is also evident in the OGO-2 results. In addition, a similar asymmetry in the high latitude distributions of both $n(H^+)$ and $n(He^+)$ was identified in the OGO-2 ion composition results. In the OGO-2 data, $n(He^+)$ in the northern (winter) high latitude region was observed to be higher by as much as a factor of 3-4 relative to the southern (summer) hemisphere concentrations, at latitudes (60°-80° dipole) and altitudes (800-1000 km), similar to those of the present observations. Similarly, the OGO-2 results also showed a relative depression (a factor of 3-4) in the northern (winter) hemisphere distributions of $n(H^+)$ poleward of the plasmapause, out of phase with the $n(He^+)$ asymmetry.

Seasonal Variation in H^+ and He^+

The seasonal variation in the light ion distributions has been examined by comparing the dusk profiles obtained in August 1967 with profiles obtained in December, 1967, under the closest possible conditions of altitude, latitude, α, and local time. In Figure 6 the results of a comparison of the seasonal variation in n(He^+) observed at identical geographic longitudes and nearly identical altitudes are shown. Clearly, although a similar pattern of n(He^+) variation with dipole latitude is exhibited in the opposite hemispheres, distinct seasonal differences between the n(He^+) distributions exist, particularly in the equatorial trough zone, where the n(He^+) trough is less pronounced in December, at $\alpha = 12°$. Considering the rapidly increasing difference in altitude between the profiles as the satellite moves away from the dipole equator, even the moderate similarity exhibited in the distributions is significant. Note that the amplitude of α is considerably different for the 2 profiles (August 6, $\alpha = 29°$; December 9, $\alpha = 12°$).

In order to demonstrate the effectiveness of the solar-magnetic seasonal control, an alternate n(He^+) profile obtained on December 10, at a longitude where the solar-magnetic season ($\alpha = 26°$) is considerably closer to that for the August 6 profile ($\alpha = 29°$), is given in Figure 7. The remarkable similarity of the n(He^+) distributions in the opposite hemispheres is quite apparent. Independent of altitude differences as great as 300 km near 50°-60° dipole latitude (north and south) the symmetry between the He^+ concentrations generally differs by less than a factor of 2. Also, the breadth and depth of the equatorial trough, as well as the general shape and position of the winter hemisphere asymmetries and the high latitude winter troughs are striking in similarity. Thus, under certain conditions, it appears possible to relate solar angle and magnetic field tilt, so as to 'match' the effects of otherwise different seasons on the n(He^+) distributions. It is emphasized that throughout a wide range of altitude (500-900 km) which would be expected to span regions of both chemical and diffusive equilibrium control for n(He^+), the latitudinal variation of the helium ions appears to be dominated by solar-magnetic field oriented effects, and that

$n(He^+)$ is apparently distributed independent of altitude variations.

A similar observation may be drawn relative to the seasonal variation of $n(H^+)$, which is illustrated in Figure 8. In this plot, $n(H^+)$ profiles obtained simultaneously with the $n(He^+)$ profiles of Figure 7 are compared. Although concentrations of H^+ observed at $\alpha = 29°$ are generally higher by a factor of at least 2-3 at all latitudes, the latitudinal variation exhibited in the 2 profiles is remarkably similar and apparently independent of altitude, which is quite different at most latitudes.

Long Term Variations in $n(H^+)$ and $n(He^+)$

Recognizing the pronounced solar-geomagnetic influence exhibited in the H^+ and He^+ concentrations, a set of $n(H^+)$ and $n(He^+)$ profiles obtained in December 1967 and December 1968, has been selected, again on the basis of best possible agreement in altitude, latitude, local time, and α. The restrictions imposed in the selection process have limited the time span of the sample, illustrated in Figures 9 and 10, to a period of 1 year. These data, which were obtained during a period of rising solar activity were nevertheless obtained uder conditions of similar magnetic activity (Kp = 2-3).

In Figure 9 the agreement between the 2 $n(He^+)$ distributions obtained one year apart is rather remarkable. The primary variations in the $n(He^+)$ profiles, including the equatorial and high latitude trough, are surprisingly similar. The $n(H^+)$ profiles shown in Figure 10 exhibit somewhat larger differences between December 1967 and December 1968, although these differences are also observed to be comparable to the range of variability observed between orbits on a given day. In both Figures 9 and 10, the more pronounced differences in He^+ and H^+ concentrations, observed above about +40°N, are most likely attributable in part to the necessity of 'splicing' the -51° long. profile segment onto the profile obtained at -75° longitude. Of primary interest is the fact that, in general, the respective levels of $n(He^+)$ and $n(H^+)$ in the altitude range 500-900 km are not significantly different between the 2 years, illustrating that at this location, there is no evidence of a trend toward the formation of a dominant He^+ belt. The differences in $n(He^+)$ which are exhibited between the 2 profiles are well within the orbit-to-orbit variability observed in $n(He^+)$ during even magnetically quiet days ($Kp \leq 2$). For convenient reference the $n(H^+)$ and $n(He^+)$ profiles observed in December 1967-68 are plotted together, in Figure 11. The dominance of $n(H^+)$ over $n(He^+)$ at all latitudes, with the exception of a rather narrow interval (10°-15° dipole) in the winter hemisphere (at maximum α values), is generally characteristic of the composition results examined to date, in the altitude range 600-900 km, during both day and night. The variability in $n(H^+)/n(He^+)$ observed over the entire data sample is such that the selection of a representative value or even a narrow range of values is not meaningful.

DISCUSSION

The evidence of the existence of

(1) a pronounced equatorial trough in $n(He^+)$, accompanied by a lesser trough in $n(H^+)$,

(2) a large scale asymmetry or bulge in which the winter hemisphere concentrations of He^+ are enhanced by a factor of 4 or more relative to summer hemisphere levels, and

(3) substantial variations in the position and depth of the high latitude troughs in $n(H^+)$ and $n(He^+)$

presents a distinct challenge to theories upon which present ionospheric models are based. On the basis of rather limited, and irregularly spaced satellite investigations of the composition of the topside ionosphere, conducted with both direct and indirect techniques, a very incomplete and sometimes confusing empirical picture has been formed. Combining the results of ion composition, topside sounder, and vlf research, numerous studies have previously indicated that at latitudes below the plasmapause, i.e., within the plasmasphere, the upper ionosphere is in general, largely regulated by diffusive equilibrium [Angerami and Thomas, 1964] [Thomas and Dufour, 1965] [Carpenter, 1966] [Taylor et al., 1968] [Colin and Dufour, 1968] and others.

Such studies have, of course, intended to concentrate on that region of the ionosphere which, for the primary ions, was believed to lie above the altitude range within which the ion distributions are thought to be controlled by chemical reactions. The altitude regime of chemical equilibrium for each of the 4 primary ions of the upper ionosphere is not equally well known, however. Thus, while extensive measurements of the distribution of O^+ with altitude have been made, at numerous locations, the distributions of the lesser ions, particularly He^+ and N^+, have been sampled very sparsely and are, therefore, less completely understood [Bauer, 1966b]. Accordingly, the comparison of past results obtained over a wide variety of altitudes, latitudes and longitudes provides an uncertain basis upon which to examine the present results.

Clearly, assuming that chemical control of $n(H^+)$ and $n(He^+)$ terminates below, say 600 km [Bauer, 1966a] the evidence of the equatorial troughs in $n(He^+)$ and $n(H^+)$, observed to exist at altitudes as great as 900 km and to be formed and dissipated at different magnetic-season positions <u>independent</u> of altitude variations, appears to contradict the assumption of diffusive equilibrium, even at equatorial and low latitudes. Similarly, the evidence of a winter bulge in $n(He^+)$, also apparently formed independent of altitude variation, seems to contradict diffusive equilibrium control.

Recent evidence of significant variations in the behavior of the neutral atmosphere may provide important insight into mechanisms which may, in part, be responsible for the apparent deviation from diffusive equilibrium control within the thermosphere.

First, the evidence presented by Keating and Prior [1968] of a winter bulge in neutral helium, wherein the concentrations of He may be greater by a factor of 4 relative to summer hemisphere He concentrations, appears to provide an important source for the enhancement of $n(He^+)$. Specifically, if neutral helium concentrations are significantly enhanced toward the winter pole, attendant, possibly, with a relative reduction in the concentrations of N_2 and O_2, a significant increase in the production of He^+, due both to (1) increased direct ionization of He and (2) reduced charge exchange of He^+ with either N_2 or O_2, must be expected. The present data suggest the interesting possibility that, as in the case of the He^+ asymmetry, the neutral helium bulge may also be observed to exhibit some variability with respect to α.

Second, the presence of a global neutral wind at thermospheric heights (100-700 km) described by Kohl and King [1967] provides a mechanism for mass redistribution of ionization at F-region altitudes and above. In a companion paper, Brinton et al., [1969] present data on the longitudinal dependency exhibited in the O^+ - H^+ transition level, which strongly suggests that at longitudes corresponding to large values of α, O^+ is moved to lower altitudes, in the 'magnetic-winter' hemisphere, by the action of neutral winds which produce field aligned, downward directed ion drag velocities. Evidence of the same effect has been observed in the form of pronounced variations of $n(O^+)$ for widely different values of α, near 700-900 km in the OGO-4 ion data. This evidence, which is quite similar to the effects of geomagnetic control observed by Bowen et al., [1964] suggests a very probable mechanism which may significantly modify the control of diffusive equilibrium, within the plasmasphere. These and other possible mechanisms, including the very probable effects of upward and downward H^+ and He^+ fluxes induced through the coupling of the topside ionosphere and the protonosphere, as well as the effects of large scale electric fields and latitudinal temperature gradients complicate both the investigation and the interpretation of the variability of the light ions during a solar cycle. In addition, there is the added complication that the available data have been obtained during portions of 2 cycles which are quite different in terms of solar activity.

In Figure 11 a summary of reported information on the $n(H^+)/n(He^+)$ ratio is presented, relative to the solar activity observed in cycles 19 and 20. As pointed out earlier by Istomin [1966], the observational results obtained during the latter portion of cycle 19 are apparently inconsistent with the theoretical predictions, in that the Ariel-1 results [Bowen et al., 1964] indicate a major He^+ belt in a declining period (May 1962) near solar minimum. Later results obtained at solar minimum and during the early portion of cycle 20 are, on the other hand, relatively consistent and in agreement with the predicted dominance of H^+. The present results, obtained near the expected solar maximum, do not appear to support the predicted ascendancy of a global He^+ belt. It is, of course, clear that the solar activity at the time of the latest results (December 1968) was far lower than that at the time of the observations from Explorer-8 (December 1959). Nevertheless, the present results, which show no He^+ belt, were obtained at a solar activity level considerably greater than that during which the Ariel-1 results (April 1962) indicated a dominant He^+ belt near 1000 km.

Clearly, the attack on the problem of explaining the dependency of the light ion composition on solar activity is still in an early stage. The resolution of questions regarding the comparability of solar cycles and the phase relationship between solar changes and resultant changes in the ion composition, must await the availability and interpretation of greater quantities of both ion and neutral composition and temperature data, obtained under comparable conditions of altitude, latitude, longitude and season.

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FIGURES

Figure 1: Pertinent characteristics of OGO-4 orbit, during August 1-7 and December 8-10, 1967. Approximate local times corresponding to dawn-dusk equator crossings are shown, with approximate solar elevation angles for these dates. In data discussions, the August 1-7 period is referred to as 'summer' even though the solar elevation is not maximum.

Figure 2: Latitudinal distributions of the primary ion distributions observed on August 6, 1967, in the interval 2050 U.T. to 2139 U.T.

Figure 3: Isometric coordinate display of the longitudinal variability observed in latitudinal distributions of $n(He^+)$ during the period August 1-7, 1967. A typical altitude-latitude profile, which is characteristic of these data is shown at +136° longitude. Due to gaps in data availability, some distributions are necessarily not sequential. Maximum altitude variation between distributions (at any given latitude) is within 130 km. Note broadening and deepening of equatorial $n(He^+)$ trough near maximum values of α (defined as the angle between the earth-sun line and the dipole equator). During the period of these data magnetic activity was quiet-to-moderately disturbed (maximum Kp recorded was Kp = 3-).

Figure 4: Comparison of $n(He^+)$ distributions obtained August 6, 1967, at widely different longitudes and correspondingly different values of α. At $\alpha = 29°$, data extends from 2050 U.T. to 2139 U.T.; at $\alpha = 5°$, 0931 U.T. to 1020 U.T.

Figure 5: Comparison of $n(H^+)$ distributions obtained simultaneously with the data shown in Figure 4.

Figure 6: Comparison of seasonal influence exhibited in $n(He^+)$ distributions obtained on August 6, 1967 (2050 U.T. to 2139 U.T.) and December 9, 1967 (2038 U.T. to 2128 U.T.). North-south positions of distributions are shown opposed, to emphasize similarity of seasonal influence. Note that data were obtained at identical longitudes and very similar local times, but at significantly different values of α and altitude. Both August 6 and December 9 were quiet-to-moderately disturbed magnetically (Kp = 2-3).

Figure 7: Comparison of seasonal influence exhibited in $n(He^+)$ distributions obtained on August 6, 1967 (2050 U.T. to 2139 U.T.) and December 10, 1967 (1429 to 1519 U.T.). As in Figure 5, north-south positions of distributions are shown opposed. Data were obtained at widely different longitudes but at much closer values of α, relative to the α positions of the data of Figure 5. Note the strikingly similar seasonal asymmetry exhibited, at widely different altitudes. Both August 6 and December 10 were quiet-to-moderately disturbed magnetically (Kp = 2-3).

Figure 8: Comparison of seasonal influence exhibited in $n(H^+)$, observed simultaneously with the data shown in Figure 6. Note the great similarity in the seasonal asymmetry exhibited, at widely different altitudes.

Figure 9: Comparison of long term variability in $n(He^+)$ between December 9,

1967 (2038 U.T. to 2128 U.T.) and December 31, 1968 (1821 U.T. to 2013 U.T.), under closest possible conditions of altitude, local time and α. Due to gaps in available data, the He^+ distribution obtained on December 31 is necessarily composed of segments of 2 consecutive orbits. Both days were quiet-to-moderately disturbed magnetically (Kp = 2-3).

Figure 10: Long term variability in $n(H^+)$ distributions observed simultaneously with the $n(He^+)$ distributions shown in Figure 9.

Figure 11: An illustration of the long term variability observed in $n(H^+)/n(He^+)$. These are the same results included in Figures 9 and 10.

Figure 12: Observations bearing on the response of $n(H^+)/n(He^+)$ to changing solar activity. The dominant ion observed near 1000 km is indicated above the time of each observation.

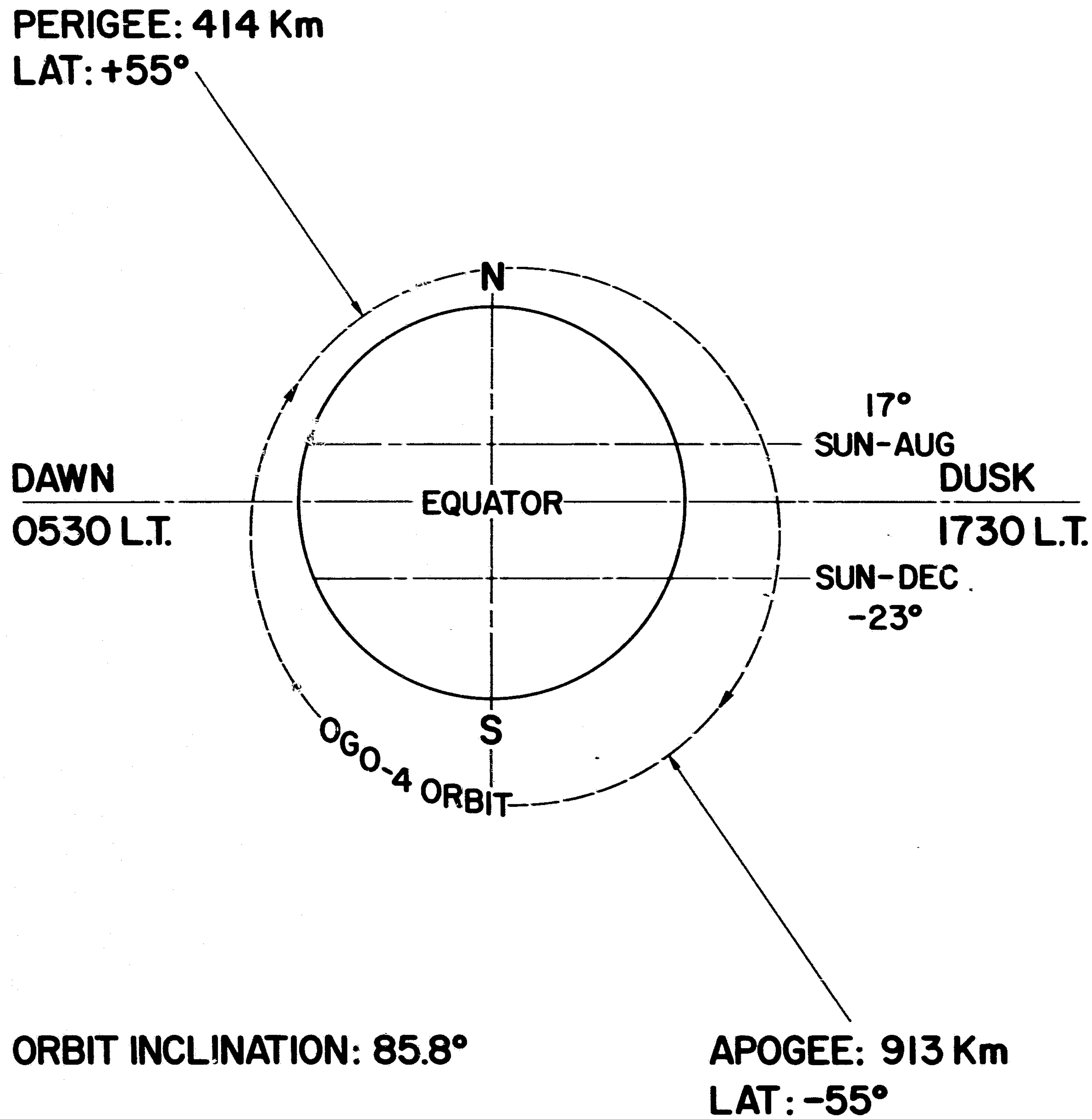

PERIGEE: 414 Km
LAT: +55°
N
17°
SUN-AUG
DAWN
0530 L.T.
EQUATOR
DUSK
1730 L.T.
SUN-DEC
-23°
S
OGO-4 ORBIT
ORBIT INCLINATION: 85.8°
APOGEE: 913 Km
LAT: -55°

Figure 1

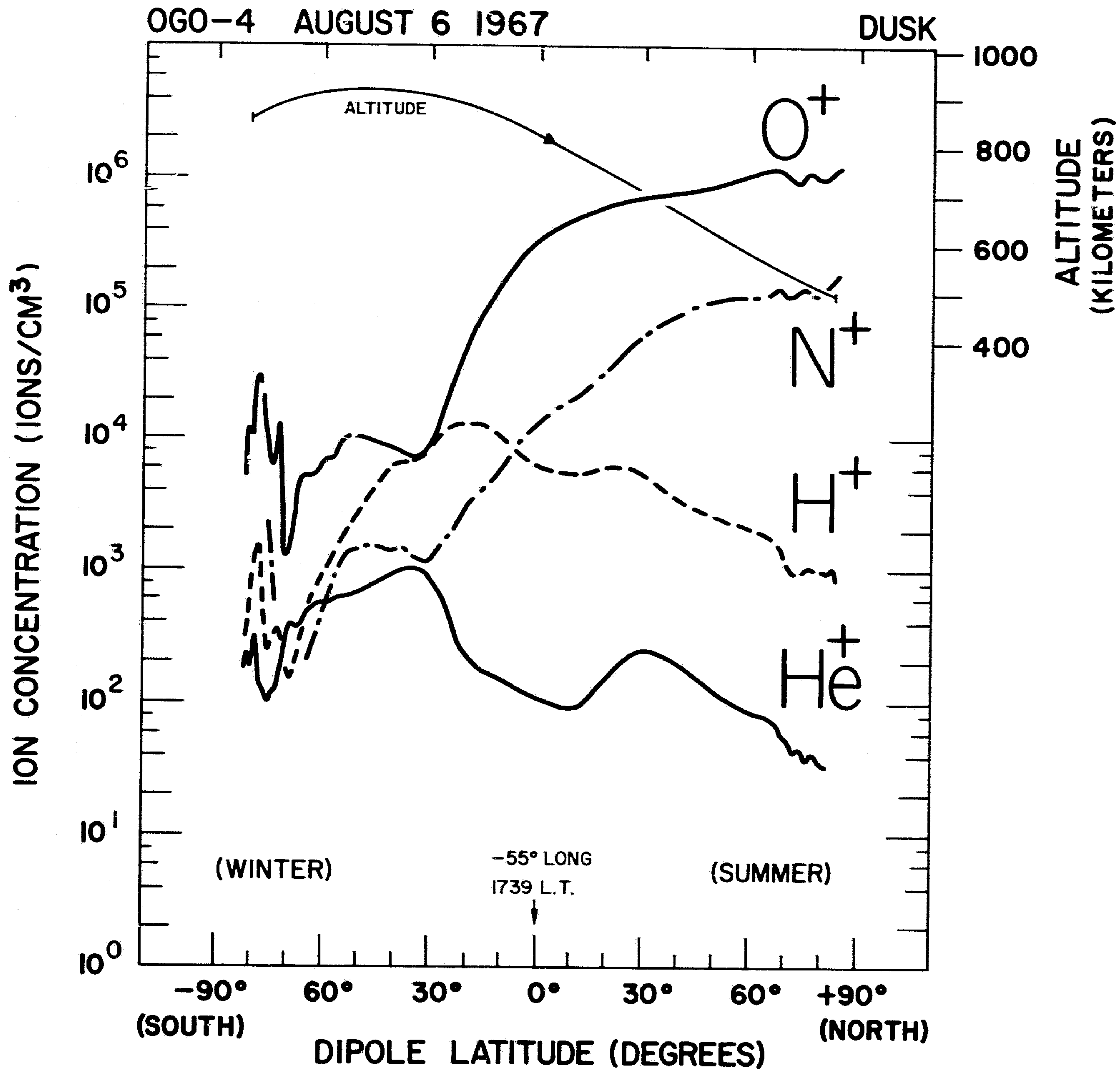

OGO-4 AUGUST 6 1967
DUSK
ALTITUDE
O+
N+
H+
He+
10^0
10^1
10^2
10^3
10^4
10^5
10^6
ION CONCENTRATION (IONS/CM³)
1000
800
600
400
ALTITUDE (KILOMETERS)
(WINTER)
−55° LONG
1739 L.T.
(SUMMER)
−90°
60°
30°
0°
30°
60°
+90°
(SOUTH)
(NORTH)
DIPOLE LATITUDE (DEGREES)

Figure 2

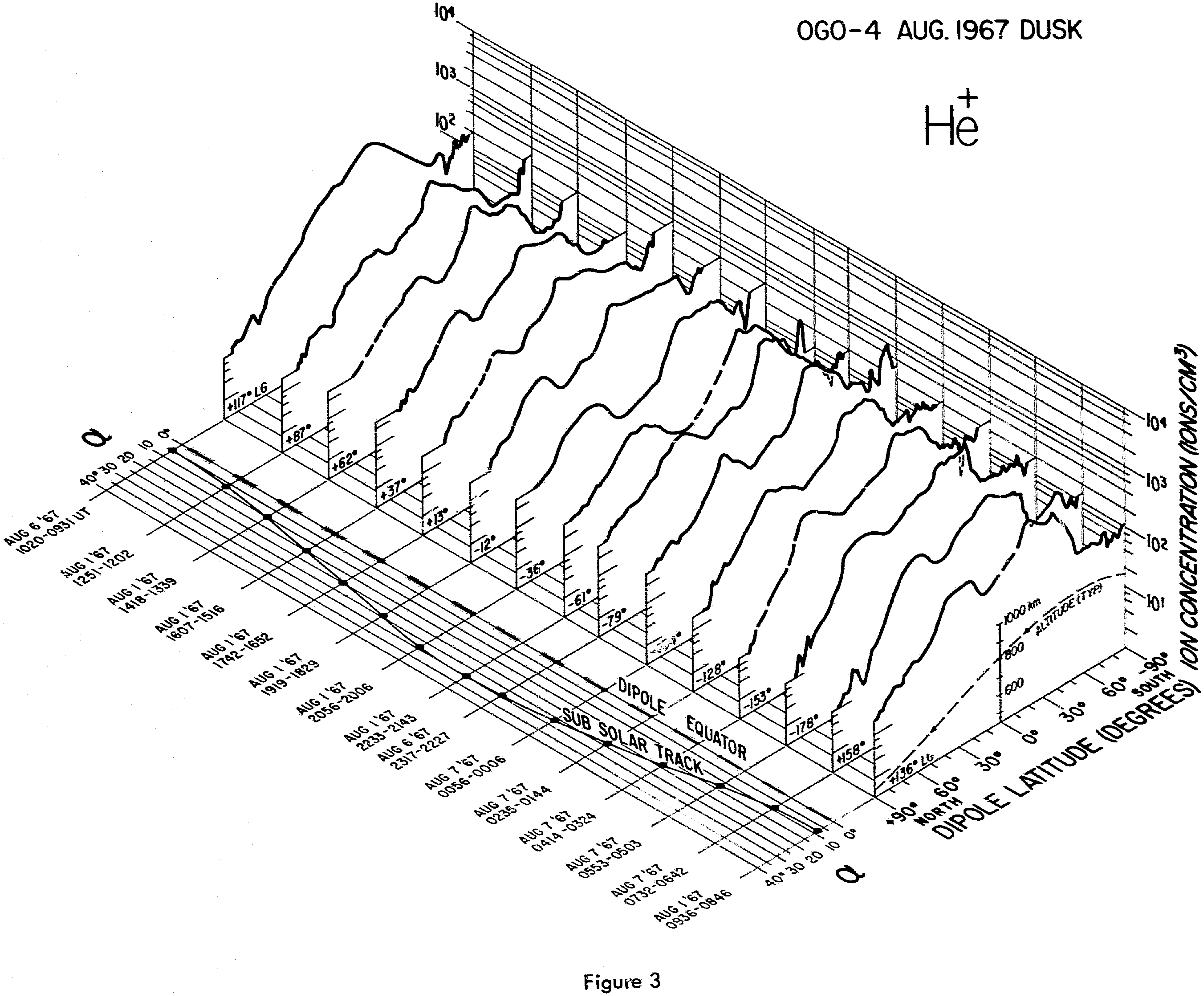

OGO-4 AUG. 1967 DUSK
He^+
ION CONCENTRATION (IONS/CM^3)
DIPOLE LATITUDE (DEGREES)
+90° NORTH 60° 30° 0° 30° 60° -90° SOUTH
DIPOLE EQUATOR
SUB SOLAR TRACK
ALTITUDE (TYP)
1000 km
800
600
α
40° 30 20 10 0°
AUG 6 '67 1020-0931 UT
AUG 1 '67 1251-1202
AUG 1 '67 1418-1339
AUG 1 '67 1607-1516
AUG 1 '67 1742-1652
AUG 1 '67 1919-1829
AUG 1 '67 2056-2006
AUG 1 '67 2233-2143
AUG 6 '67 2317-2227
AUG 7 '67 0056-0006
AUG 7 '67 0235-0144
AUG 7 '67 0414-0324
AUG 7 '67 0553-0503
AUG 7 '67 0732-0642
AUG 1 '67 0936-0846
+117° LG
+87°
+62°
+37°
+13°
-12°
-36°
-61°
-79°
-128°
-153°
-178°
+158°
+136° LG

Figure 3

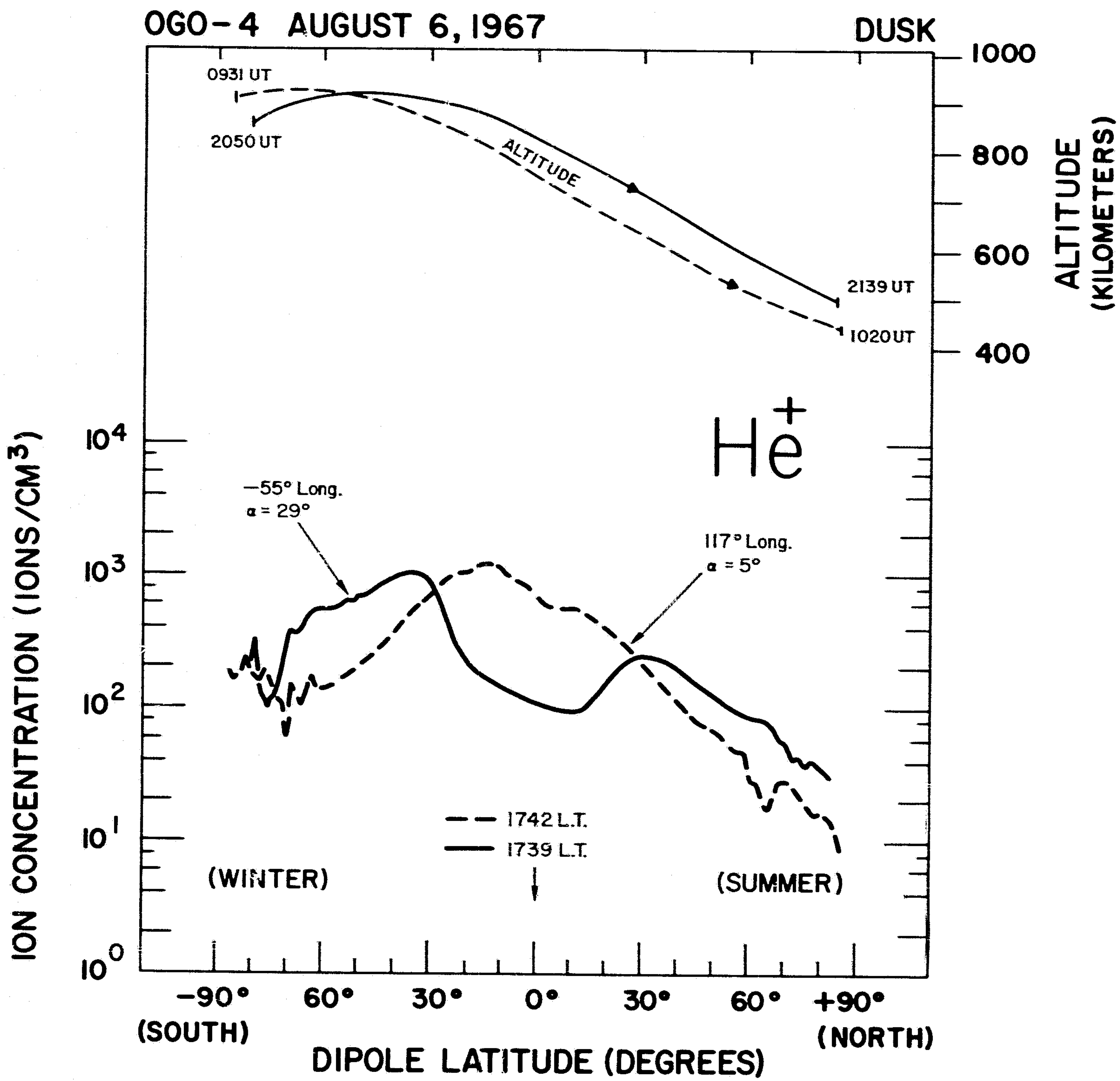

OGO-4 AUGUST 6, 1967
DUSK
0931 UT
2050 UT
ALTITUDE
2139 UT
1020 UT
1000
800
600
400
ALTITUDE (KILOMETERS)
He+
−55° Long.
α = 29°
117° Long.
α = 5°
1742 L.T.
1739 L.T.
(WINTER)
(SUMMER)
ION CONCENTRATION (IONS/CM3)
10^4
10^3
10^2
10^1
10^0
−90°
60°
30°
0°
30°
60°
+90°
(SOUTH)
(NORTH)
DIPOLE LATITUDE (DEGREES)

Figure 4

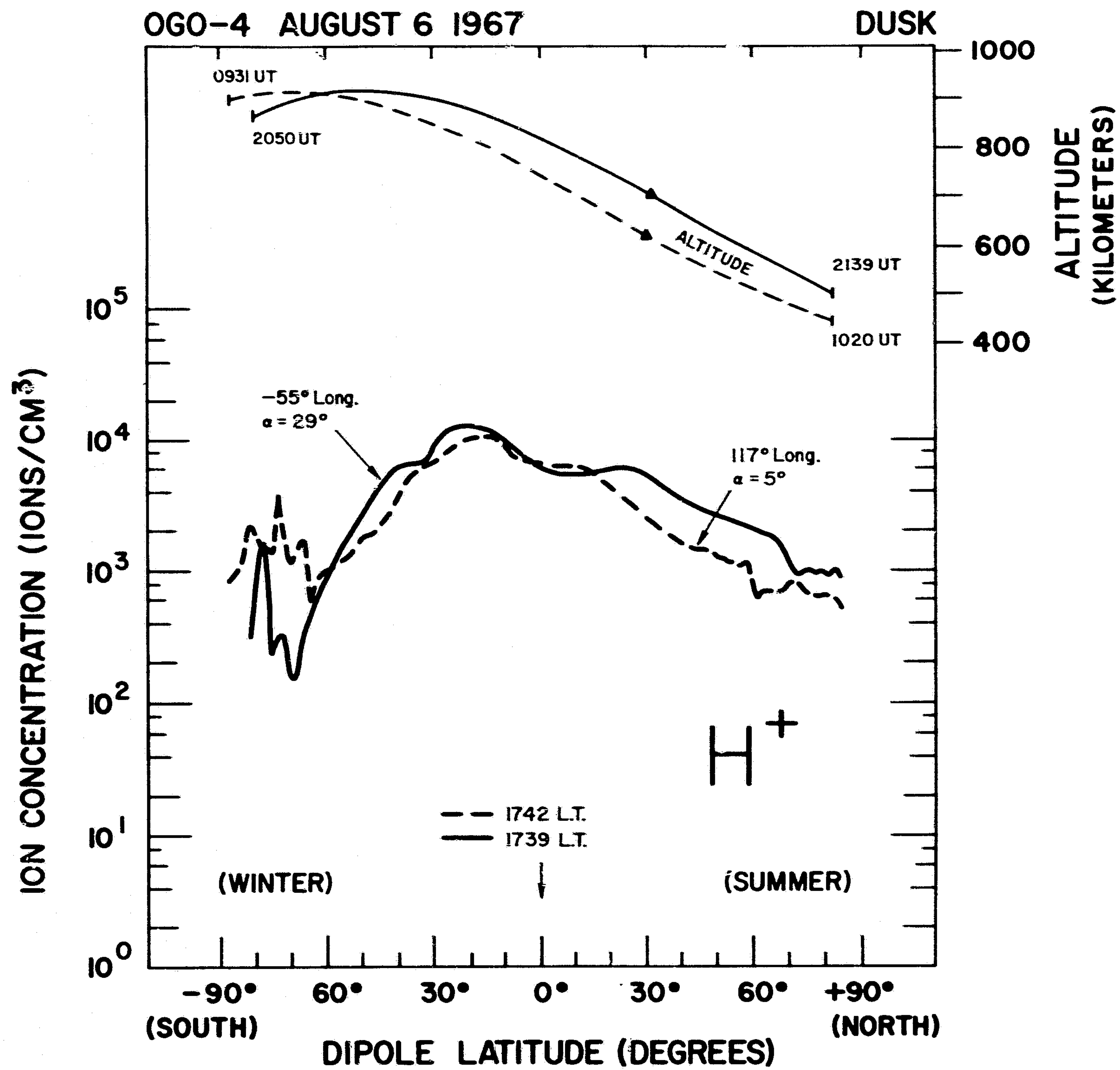
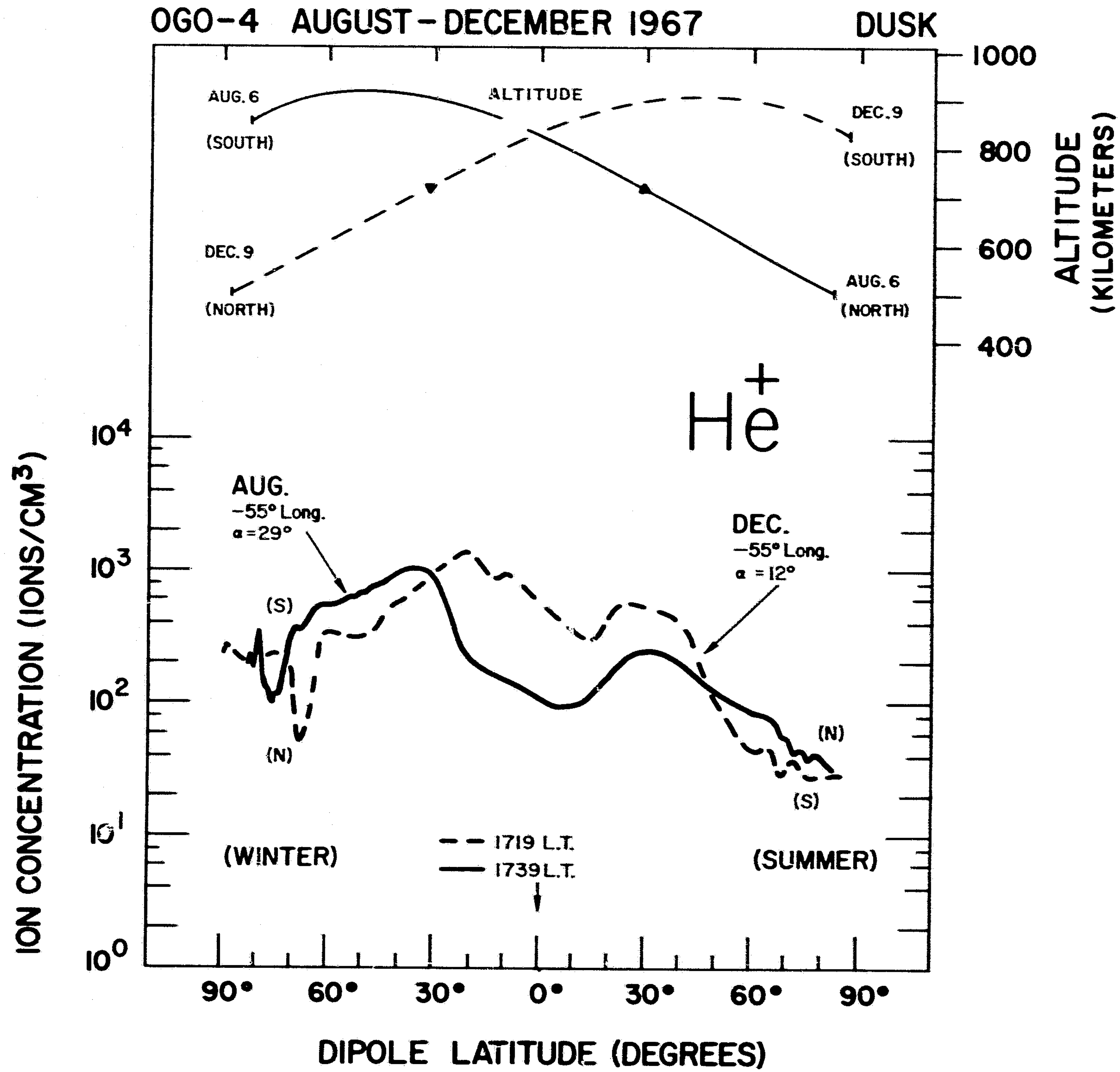
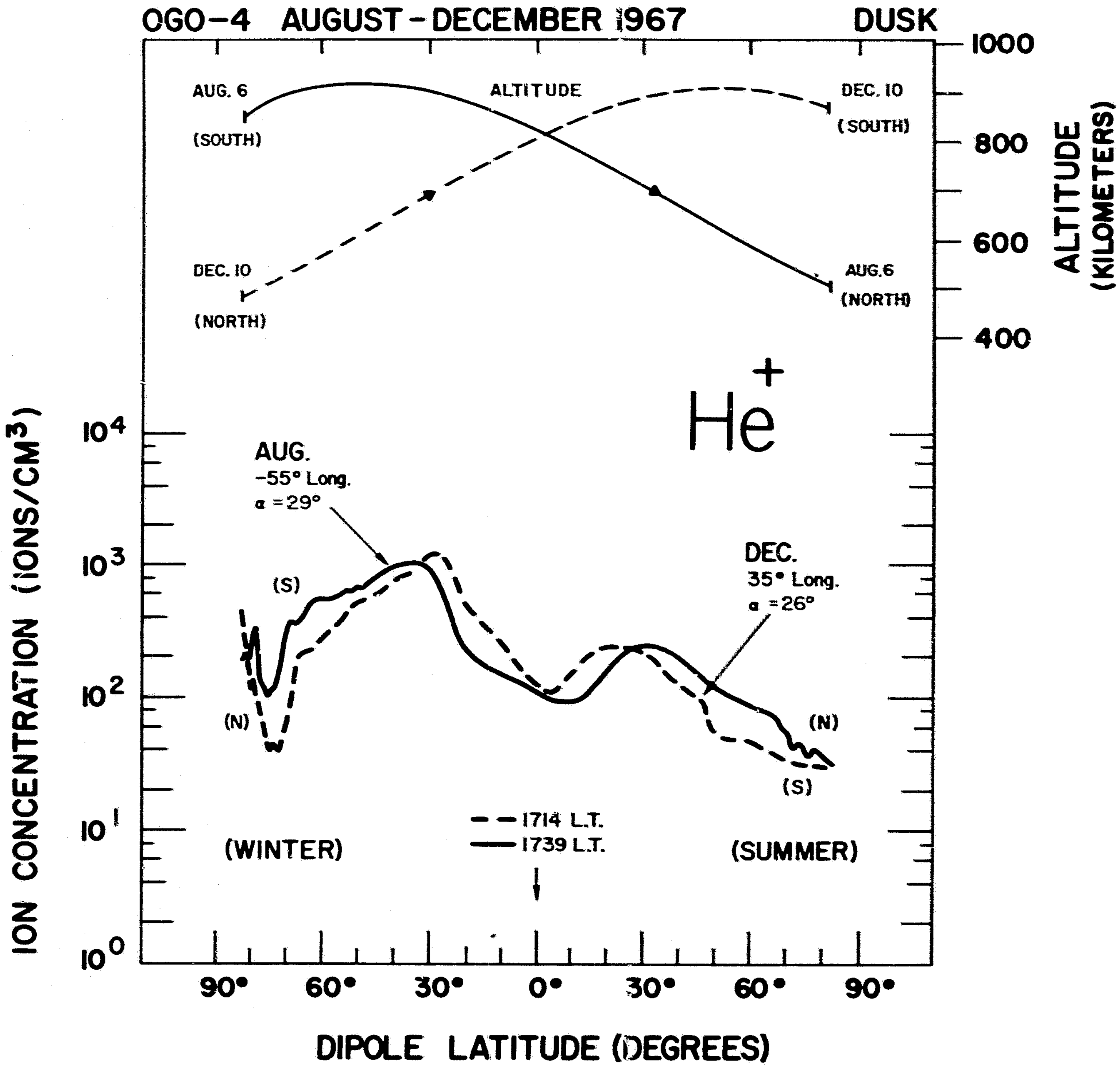

OGO-4 AUGUST 6 1967
DUSK
0931 UT
2050 UT
2139 UT
1020 UT
ALTITUDE
ALTITUDE (KILOMETERS)
1000
800
600
400
ION CONCENTRATION (IONS/CM³)
10⁵
10⁴
10³
10²
10¹
10⁰
−55° Long.
α = 29°
117° Long.
α = 5°
H⁺
1742 L.T.
1739 L.T.
(WINTER)
(SUMMER)
−90°
60°
30°
0°
30°
60°
+90°
(SOUTH)
(NORTH)
DIPOLE LATITUDE (DEGREES)

Figure 5



OGO-4 AUGUST-DECEMBER 1967
DUSK
ALTITUDE
AUG. 6
(SOUTH)
DEC. 9
(SOUTH)
DEC. 9
(NORTH)
AUG. 6
(NORTH)
1000
800
600
400
ALTITUDE (KILOMETERS)
He+
AUG.
-55° Long.
α = 29°
DEC.
-55° Long.
α = 12°
(S)
(N)
(N)
(S)
(WINTER)
(SUMMER)
1719 L.T.
1739 L.T.
ION CONCENTRATION (IONS/CM3)
10^4
10^3
10^2
10^1
10^0
90°
60°
30°
0°
30°
60°
90°
DIPOLE LATITUDE (DEGREES)

Figure 6



OGO-4 AUGUST-DECEMBER 1967
DUSK
AUG. 6
(SOUTH)
ALTITUDE
DEC. 10
(SOUTH)
DEC. 10
(NORTH)
AUG.6
(NORTH)
1000
800
600
400
ALTITUDE (KILOMETERS)
He+
AUG.
-55° Long.
α =29°
DEC.
35° Long.
α =26°
(S)
(N)
(N)
(S)
(WINTER)
(SUMMER)
1714 L.T.
1739 L.T.
ION CONCENTRATION (IONS/CM3)
10^4
10^3
10^2
10^1
10^0
90°
60°
30°
0°
30°
60°
90°
DIPOLE LATITUDE (DEGREES)

Figure 7

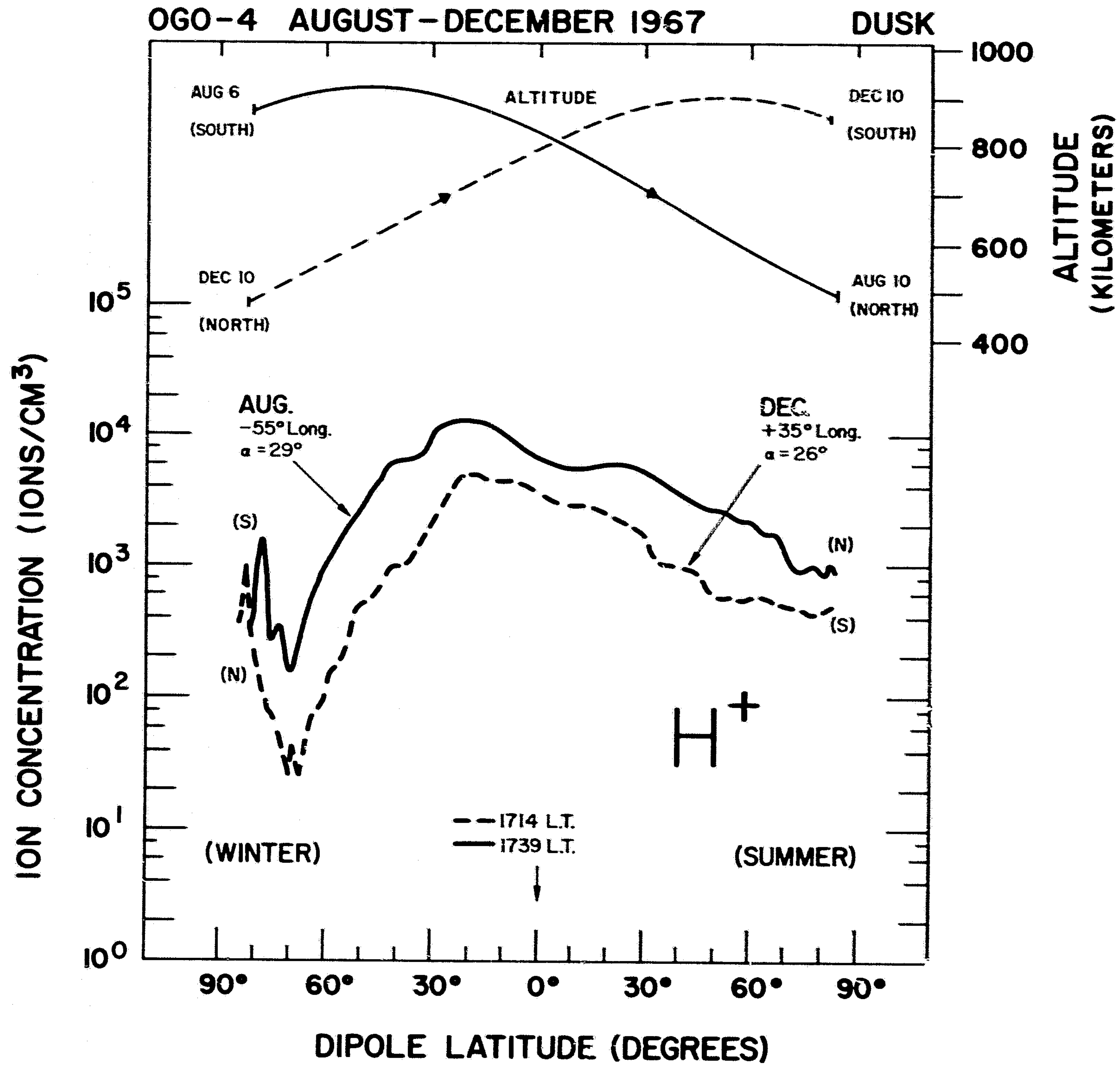
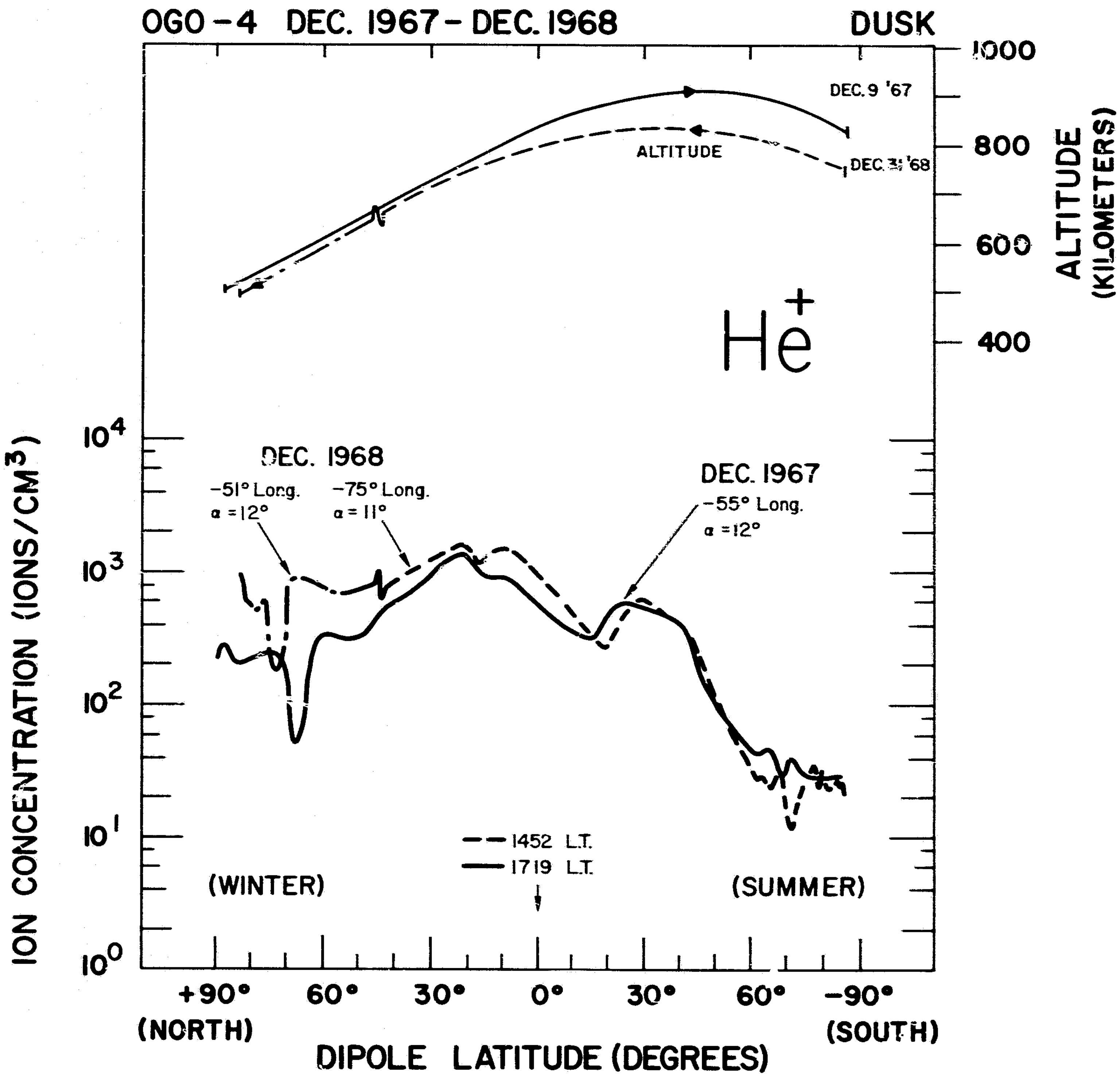

OGO-4 AUGUST-DECEMBER 1967
DUSK
AUG 6
(SOUTH)
ALTITUDE
DEC 10
(SOUTH)
DEC 10
(NORTH)
AUG 10
(NORTH)
1000
800
600
400
ALTITUDE (KILOMETERS)
ION CONCENTRATION (IONS/CM^3)
10^5
10^4
10^3
10^2
10^1
10^0
AUG.
-55° Long.
α = 29°
DEC.
+35° Long.
α = 26°
(S)
(N)
(N)
(S)
H^+
1714 L.T.
1739 L.T.
(WINTER)
(SUMMER)
90°
60°
30°
0°
30°
60°
90°
DIPOLE LATITUDE (DEGREES)

Figure 8



OGO-4 DEC. 1967-DEC. 1968
DUSK
1000
800
600
400
ALTITUDE (KILOMETERS)
DEC. 9 '67
DEC. 31 '68
ALTITUDE
He^+
10^4
10^3
10^2
10^1
10^0
ION CONCENTRATION (IONS/CM^3)
DEC. 1968
−51° Long.
α = 12°
−75° Long.
α = 11°
DEC. 1967
−55° Long.
α = 12°
1452 L.T.
1719 L.T.
(WINTER)
(SUMMER)
+90°
60°
30°
0°
30°
60°
−90°
(NORTH)
(SOUTH)
DIPOLE LATITUDE (DEGREES)

Figure 9

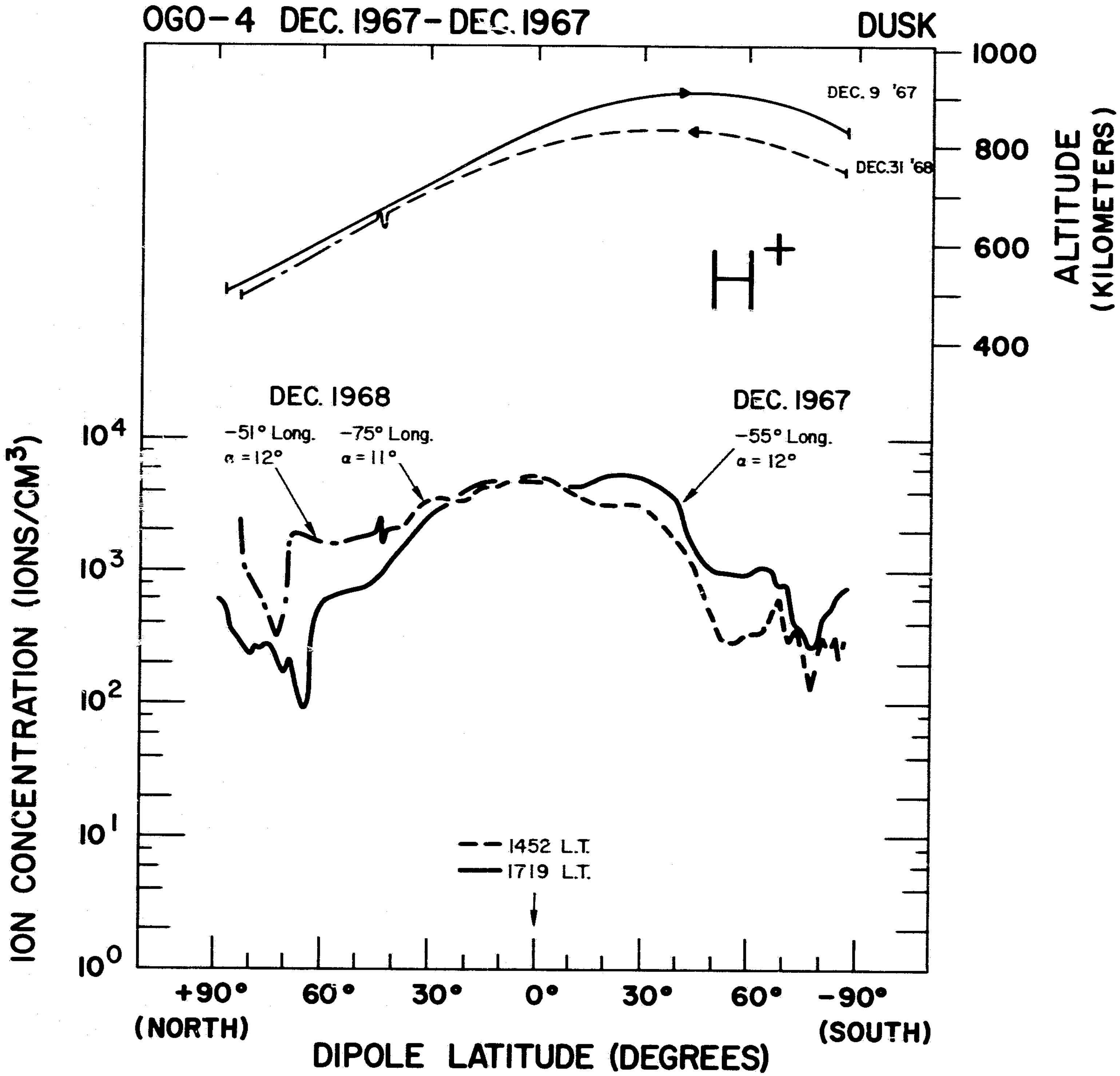
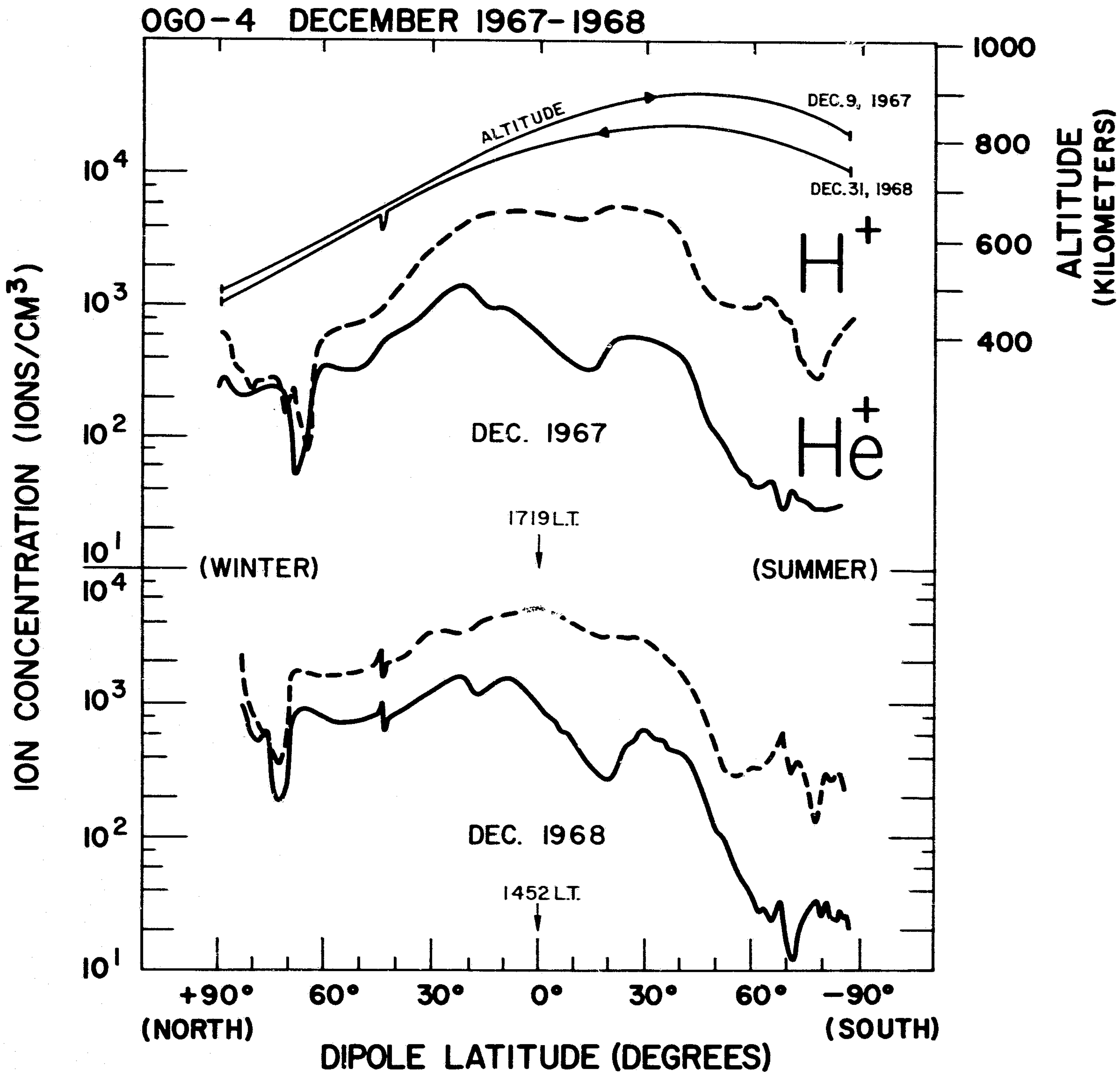
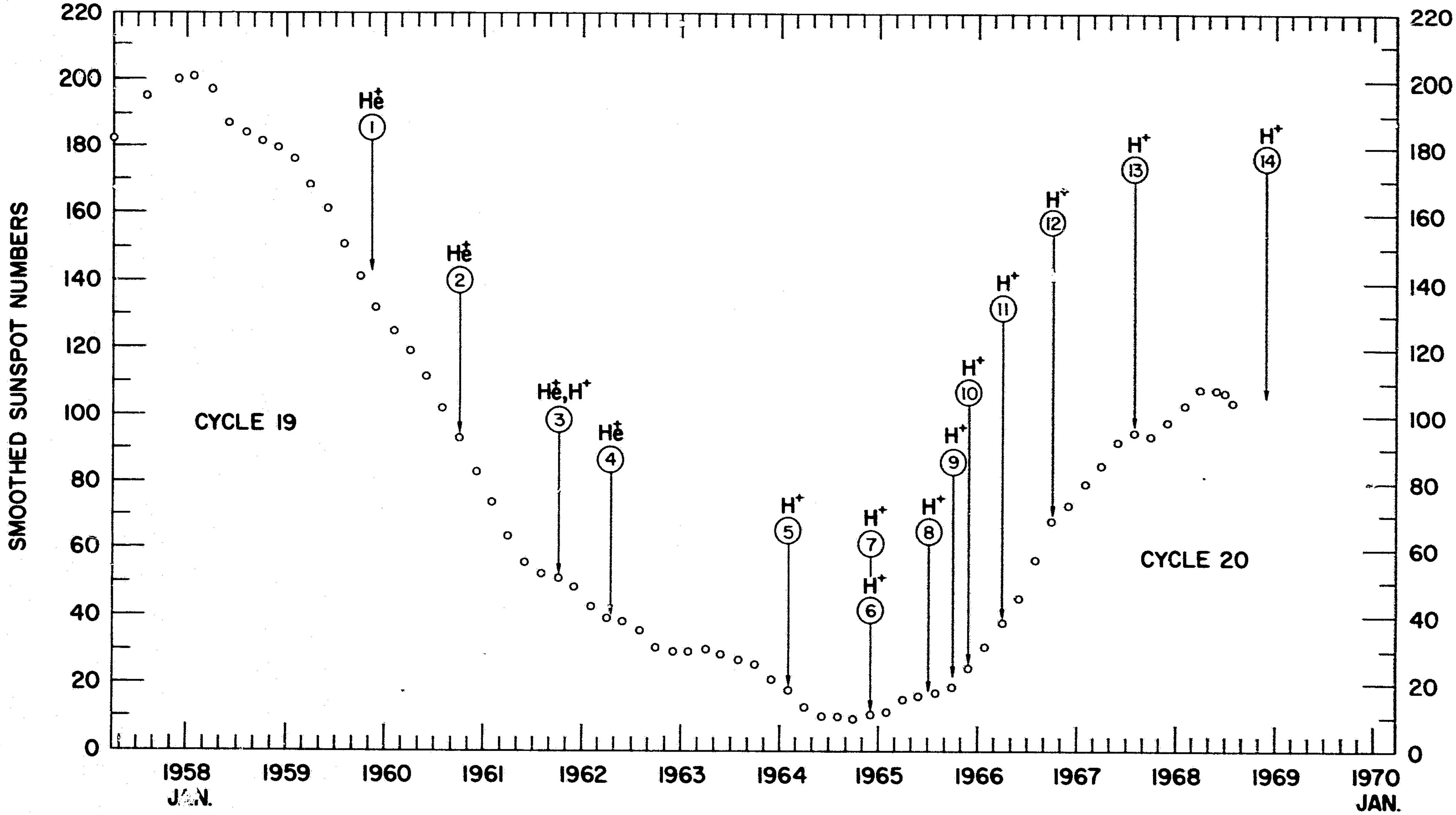

OGO-4 DEC. 1967 - DEC. 1967
DUSK
DEC. 9 '67
DEC.31 '68
H+
ALTITUDE (KILOMETERS)
1000
800
600
400
DEC. 1968
-51° Long.
α = 12°
-75° Long.
α = 11°
DEC. 1967
-55° Long.
α = 12°
ION CONCENTRATION (IONS/CM3)
10^4
10^3
10^2
10^1
10^0
1452 L.T.
1719 L.T.
+90° (NORTH)
60°
30°
0°
30°
60°
-90° (SOUTH)
DIPOLE LATITUDE (DEGREES)

Figure 10



OGO-4 DECEMBER 1967-1968
ALTITUDE
DEC. 9, 1967
DEC. 31, 1968
1000
800
600
400
ALTITUDE (KILOMETERS)
H^+
He^+
DEC. 1967
1719 L.T.
(WINTER)
(SUMMER)
DEC. 1968
1452 L.T.
ION CONCENTRATION (IONS/CM^3)
10^4
10^3
10^2
10^1
+90° (NORTH)
60°
30°
0°
30°
60°
-90° (SOUTH)
DIPOLE LATITUDE (DEGREES)

Figure 11



(1) EXPLORER-8 ION TRAP (BOURDEAU)
(2) ROCKET-ION TRAP (HANSON-HALE)
(3) ROCKET-ION SPEC. (TAYLOR)
(4) ARIEL-1 ION PROBE (BOWEN)
(5) ELECTRON-2 ION SPEC. (ISTOMIN)
(6) ARECIBO RADAR (CARLSON)
(7) ALOUETTE-2 VLF (McEWEN)
(8) ARECIBO RADAR (CARLSON)
(9) OGO-2 ION SPEC. (TAYLOR)
(10) JICAMARCA RADAR (FARLEY)
(11) OGO-2 ION SPEC. (TAYLOR)
(12) EXPLORER-32 ION SPEC. (BRINTON)
(13) OGO-4 ION SPEC. (TAYLOR)
(14) OGO-4 ION SPEC. (TAYLOR)

Figure 12