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S. A. Gonzales

Bela G. Fejer, *Utah State University*

R. A. Heelis

W. B. Hanson



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Ion Composition of the Topside Equatorial Ionosphere During Solar Minimum

S. A. GONZÁLEZ AND B. G. FEJER

Center for Atmospheric and Space Sciences, Utah State University, Logan

R. A. HEELIS AND W. B. HANSON

Center for Space Sciences, Physics Programs, University of Texas at Dallas, Richardson

We have used observations from both the Bennett ion mass spectrometer and the retarding potential analyzer on board the Atmosphere Explorer E satellite to study the longitudinally averaged O^+ , H^+ , and He^+ concentrations from 150 to 1100 km in the equatorial ionosphere during the 1975-1976 solar minimum. Our results suggest that the ion mass spectrometer measurements need to be increased by a factor of 2.15 to agree with the densities from the retarding potential analyzer and with ground-based measurements. The peak H^+ concentrations are about $2.5 \times 10^4 \text{ cm}^{-3}$ during the day and 10^4 cm^{-3} at night and vary little with season. The O^+/H^+ transition altitude lies between 750 and 825 km during the day and between 550 and 600 km at night. He^+ is a minor species at all altitudes; its concentration is highly variable with a maximum value of about 10^3 cm^{-3} during equinox daytime.

INTRODUCTION

For more than 20 years the relative concentrations of O^+ , H^+ , and He^+ , the three major ion species in the topside ionosphere, have been studied in situ with satellites, from the ground with incoherent scatter radars, and theoretically using computer models [e.g., *Hanson and Ortenburger*, 1961; *Farley et al.*, 1967; *Moorcroft*, 1969; *Taylor et al.*, 1968, 1970; *Brinton et al.*, 1970; *Hagen and Hsu*, 1974; *Titheridge*, 1976; *Vickrey et al.*, 1979; *Kutiev et al.*, 1980; *Breig et al.*, 1985; *Heelis et al.*, 1990]. The relative abundance of these ions is dependent on solar and magnetic activity, on latitude, and, at low and equatorial latitudes, also on longitude. These measurements have also been used to derive a number of neutral atmospheric parameters (neutral exospheric temperature, concentrations of oxygen and hydrogen atoms, etc.) [e.g., *Breig et al.*, 1981].

Recently, there has been a renewed effort to understand the temporal and seasonal behavior of the topside ion distributions as their dynamics are essential for the understanding of the coupling between the protonosphere and the topside ionosphere. *Kutiev et al.* [1980] showed that the O^+/H^+ transition altitude has a much more pronounced latitudinal dependence at solar maximum than during solar minimum. *Tepley and Kerr* [1987, 1989] used the Arecibo incoherent scatter radar (18.3°N, 66.8°W; magnetic dip 50°N) to study the temporal, seasonal, and solar cycle variations of $[H^+]$, $[O^+]$, and their fluxes at $L=1.4$. *Heelis et al.* [1990] have studied the distribution of He^+ at low latitudes and mid-latitudes using observations from the Dynamics Explorer 2 (DE 2) satellite and compared these with model calculations. They found that He^+ can be the major ion in the topside mid-latitude ionosphere near 900 km during solar maximum equinox. The H^+ , O^+ , and He^+ fractional compositions measured at the Jicamarca Radar Observatory (11.95°S, 76.87°W; magnetic dip 2°N) for the period of April 1966 have been reported by *Farley* [1991].

Over the last few years, there have been extensive coordinated incoherent scatter and optical measurements during the collaborative H alpha and radar measurements of the exosphere (CHARM) campaigns [e.g., *Kerr et al.*, 1991] to determine the dynamics of the topside ionosphere and thermosphere. All these results are important to test theoretical models of the topside ionosphere [e.g., *Bailey*, 1983; *Richards et al.*, 1983; *Richards and Torr*, 1985; *Bailey and Sellek*, 1990] that study the relative importance of solar variability, $E \times B$ drifts and F region neutral winds responsible for interhemispheric plasma transport in the topside ionosphere.

The Atmosphere Explorer E (AE-E) satellite data have been examined to determine the average behavior of the total ion concentrations and the constituent concentrations of O^+ , He^+ , and H^+ . These data are obtained from unified abstract (UA) data files containing spatially averaged values from the retarding potential analyzer (RPA) [*Hanson et al.*, 1973] and the Bennett ion mass spectrometer (BIMS) [*Brinton et al.*, 1973]. In order to study the altitude distributions of the constituent ion species we confine our attention to data taken during the elliptical phase of the AE-E mission. The average 10.7-cm solar flux during this period covering 1975 and 1976 was about $74 \times 10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$. This extended period allows examination of the seasonal dependences by separately considering December and June solstices and combining spring and fall equinoxes.

INSTRUMENTATION

The RPA aboard the AE-E satellite measures the energy distribution of the thermal ions in the direction approximately along the satellite velocity vector. A retarding potential is used to determine the ion energy that the incoming ions must exceed to reach a collector where the ion current is measured. Measurement of the ion flux as a function of retarding potential provides a description of the integral energy distribution from which the total ion concentrations, the ion temperature, and the incident ion energy can be obtained using a least squares fitting technique. In the case that ions with widely spaced masses like H^+ , He^+ , and O^+ are present with sufficient concentrations, their number densities can also be determined.

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The BIMS instrument uses RF electric fields to maximize the energy of ions of a selected mass. A stopping potential is used at the exit of the spectrometer to select only the mass receiving maximum energy. A stable electrometer detector allowed the relative concentrations of O^+ , H^+ , and He^+ to be detected along the entire AE-E orbit and over the mission's lifetime.

ANALYSIS

The data used in this study were extracted from the AE-E unified abstract (UA) files. The measurements cover the period from December 1975 to December 1976 when the AE-E orbit was highly elliptical, varying from a perigee of about 150 to an apogee near 4000 km. It took the spacecraft about 25 min. to move from perigee to about 1500 km altitude (usually, the upper altitude of the measurements was about 1200 km). Thus the UA data, with a time resolution of 15 s along the orbital track, provide a good statistical definition of the topside ionosphere from each pass. The H^+ , He^+ , and O^+ ion concentrations measured by the BIMS were then compared with the total ion concentration (n_i) derived from the RPA. A detailed study of the region around the F region peak demonstrated a consistent and repetitive disagreement between O^+ and n_i . Although the shapes of the curves agreed near the F region peak, the O^+ concentration was consistently less than half of the total ion concentration. We found that on the average, O^+ was a factor of 2.15 ± 0.06 lower than n_i (derived from the RPA) at the F region peak (between 350 and 400 km), where one would expect these two values to be the same. This is illustrated in Figure 1. From this systematic difference we concluded that the BIMS measurements should be normalized by this factor to agree with the RPA. Since all the constituent species were normalized equally, the relative abundances of the ions and specifically the transition altitude between O^+ and H^+ are not affected. Another reassuring result of this normalization is that on the topside F region the total number of ions ($\sum_j n_j$), as determined by adding the He^+ , H^+ , and O^+ concentrations, also agrees remarkably well with the density

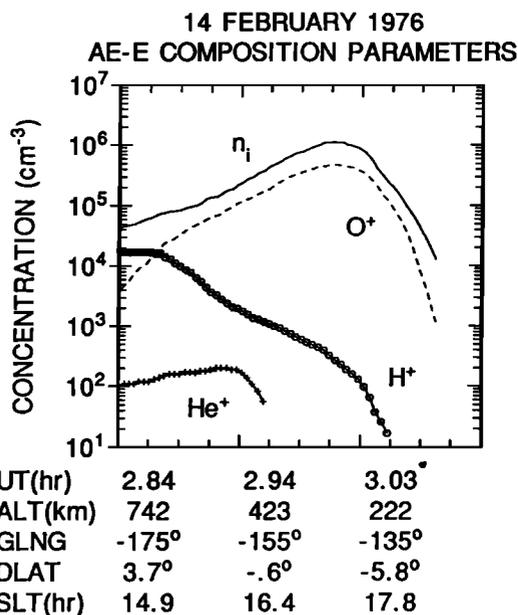


Fig. 1. Example of the O^+ , H^+ , and He^+ concentrations measured by the BIMS aboard the AE-E satellite. The total ion concentration measured by the RPA is also shown.

from the RPA. Furthermore, the total ion concentrations (from the RPA) are in good agreement with those measured over Jicamarca for similar solar conditions and also with the electron densities predicted by the international reference ionosphere (IRI) for Jicamarca and for two other longitudinal sectors. Thus we are confident that this normalization factor is necessary. Previously, *Oppenheimer et al.* [1981] pointed out that the absolute ion densities from the AE-E BIMS are somewhat uncertain. *Breig et al.* [1985] also noticed a difference in the ion concentrations from these two instruments on AE-E and concluded that $[H^+]/[O^+]$ was a factor of 1.3 too low for the BIMS entries in the AE UA files. They determined that the correction factor for H^+ was 1.95 ± 0.12 , and for O^+ it was 1.5 ± 0.07 . They did not examine the He^+ data. Their factor for H^+ is almost the same as ours; the O^+ correction, however, is too low to agree with our results. As Breig et al. utilized only 21 orbital passes in their analysis and we used almost 200, we feel that our larger constant is more reasonable. Since we have applied the same correction factor to O^+ , H^+ , and He^+ , the relative concentrations and our results on the O^+/H^+ transition altitude remain unchanged from what they would have been using the uncorrected data. The normalization was used, however, to obtain absolute values of the ionic concentrations.

For the purpose of producing average height profiles of the constituent ion concentrations, the region between 100 km and 1100 km was divided into 10 bins each 100 km in extent. Average values of $[O^+]$, $[H^+]$, and $[He^+]$ from the BIMS and the n_i from the RPA were determined for each altitude bin for selected local time and seasonal conditions. Examination of the data shows a local time variation in agreement with previous studies [e.g., *Titheridge*, 1976; *Hanson and Patterson*, 1964]. At sunrise there is a short (about 2 hours) transition period during which the ion and electron temperatures are increasing rapidly while O^+ is being produced by photoionization; the O^+/H^+ transition height rises to a level, where it remains until sunset. After sunset the ionosphere cools and $[O^+]$ decays, mostly by reactions with molecular gases. The O^+/H^+ transition height falls to a new level, where it remains until sunrise. This nighttime level is maintained by the resonant charge exchange reaction



that maintains the relative concentrations of O^+ and H^+ . Since the magnetic field lines are almost horizontal at the magnetic equator, H^+ cannot readily descend from the protonosphere. Thus changes in the transition altitude are caused primarily by production and loss of O^+ and by variations in the concentrations of neutral hydrogen and oxygen. This property of the topside ionosphere allows improvement of the statistics by collecting the data into two broad local time regions; daytime (0800 to 1800 local time) and nighttime (2000 to 0500 local time). The distribution of ions is highly dependent on latitude, and thus a single region from -7.5° to 7.5° dip latitude was chosen to provide a reasonable amount of data without compromising the latitudinal variability. We also examined the height profiles for latitudes between $\pm 5^\circ$ and $\pm 10^\circ$ and obtained essentially identical results, except that the $\pm 10^\circ$ bin began showing latitudinal effects (e.g., the Appleton peak began showing in the higher-altitude bins). Notice that a height of 1000 km at the dip equator maps to 300 km for a dip angle of 21.1° . The data are too sparse to reveal any longitudinal variations within the local time and latitude bins;

thus all longitudes are combined to further improve the statistics. Finally, three seasonal periods, December solstice (November, December, January, and February), June solstice (May, June, July, and August), and the equinoxes (March and April combined with September and October), are considered separately.

In Figure 2 we show a scatter plot of the actual profiles that were used in the December solstice, 0800-1800 LT bin for all three ions (O^+ , H^+ , and He^+). These concentrations are from the actual BIMS data in the UA files and have not been normalized. We can see that there is relatively small scatter of the individual passes around the average for both O^+ and H^+ . He^+ , however, typically shows about an order of magnitude variation about the average profile. This variability reflects the rather large local time regions over which the data are averaged as well as the fact that all longitudes are considered. In the present discussion we have described the average state of the equatorial topside ionosphere by quantifying the average ion concentrations that would be encountered by a satellite or measured by ground-based radars. The average profiles should not, however, reflect a challenge to theoretical models to be reproduced but should be used to quantitatively describe the large-scale diurnal behavior of the region. We note, for example, that what we have termed a relatively small scatter amounts to about half an order of magnitude at most altitudes. This scatter is produced by real geophysical variations within the local time and latitude ranges considered. It is known, for example, that interhemispheric plasma transport velocities are quite sensitive to variations in the F region meridional neutral winds at all longitudes [Murphy *et al.*, 1984] and to F region zonal winds as a function of longitudes [Heelis and Hanson, 1980]. Daily and longitudinal variations are included in the data shown in Figure 2, accounting for some of the observed variations. Similarly, daily and longitudinal variations in the diurnal $E \times B$ drift pattern will produce significant variations in the topside ion concentrations that appear as scatter about some mean in Figure 2.

Figure 3 shows the normalized average altitude profiles of the constituent ion concentrations and the sum of these concentrations along with the total ion concentration from the RPA. In the three top panels we show the average profiles for our three seasonal "day" bins: December, equinox, and June solstice. The statistics are best for the December solstice

because we had a total of five months of data, compared to four months for the June solstice and for the equinox. Similarly the three bottom panels show the three "night" bins. The sum of the three major ions is denoted by $\sum n_j$, and the ion concentration from the RPA is given by n_j . For some bins there were not enough data (less than 12 points) to calculate reliable averages. Thus many of the profiles do not span the entire altitude range. A slightly lower O^+/H^+ transition height is seen in the June solstice than during the December solstice or equinox. Note, however, that during the daytime the transition height occurs very near to the peak $[H^+]$ between 750 and 825 km. This is in good agreement with previous studies by Titheridge [1976] using the topside sounder from the Allouette satellite and by Farley *et al.* [1967] using incoherent scatter radar observations from Jicamarca. The AE-E observations show that $[He^+]$ is at least an order of magnitude smaller than $[H^+]$ in the topside equatorial ionosphere under daytime solar minimum conditions. Thus this species does not contribute significantly to the total ion concentrations at any altitude.

Figure 4 shows a comparison of the H^+ and He^+ concentrations at different seasons. For $[H^+]$, very little seasonal dependence is seen. At the altitudes considered, we may expect that H^+ is in chemical equilibrium with O^+ and that the variation in the peak concentration from about $2.5 \times 10^4 \text{ cm}^{-3}$ during the daytime to 10^4 cm^{-3} at night reflects the diurnal variation in the topside O^+ concentration moderated by the diurnal variation in the neutral hydrogen and oxygen altitude distributions. During the day the seasonal variation in $[He^+]$ is evident. Although the concentrations above 400 km for both solstices are roughly equal (400 ions cm^{-3} or double the nighttime), for equinox the profile reaches a maximum of about 1000 cm^{-3} , 5 times its nighttime value. This is somewhat less than that shown by Farley [1991]; in his profile the maximum measured He^+ is about $4 \times 10^3 \text{ cm}^{-3}$ and occurs at about 1200 km. However, the 10.7-cm solar flux index during the Jicamarca measurements was more than 90, higher than during our equinox period. That is also the reason for his higher transition altitude of about 1200 km, compared to 800 km in our results. During the night (2000 to 0500 LT) there was a much smaller number of measurements. Consequently, the average profiles are not as smooth (and have larger scatter bars). Thus we cannot clearly discern any general trend except

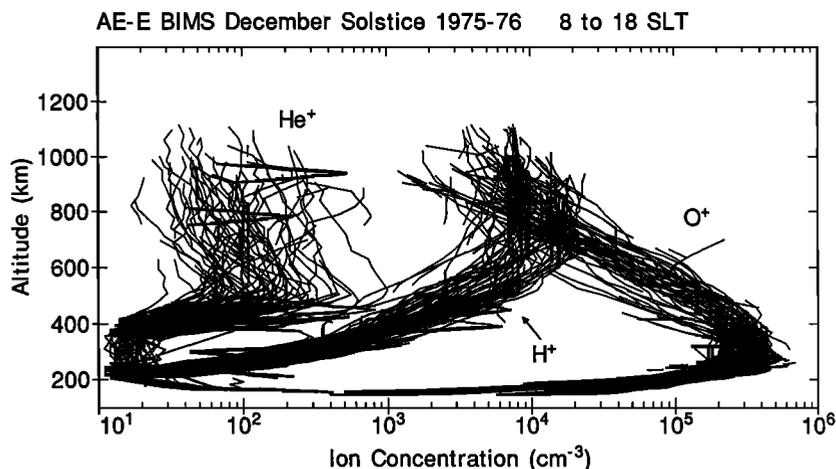


Fig. 2. Scatter plots of the main constituent species in the topside equatorial ionosphere measured by the BIMS between -7.5° and 7.5° dip latitude during the daytime December solstice.

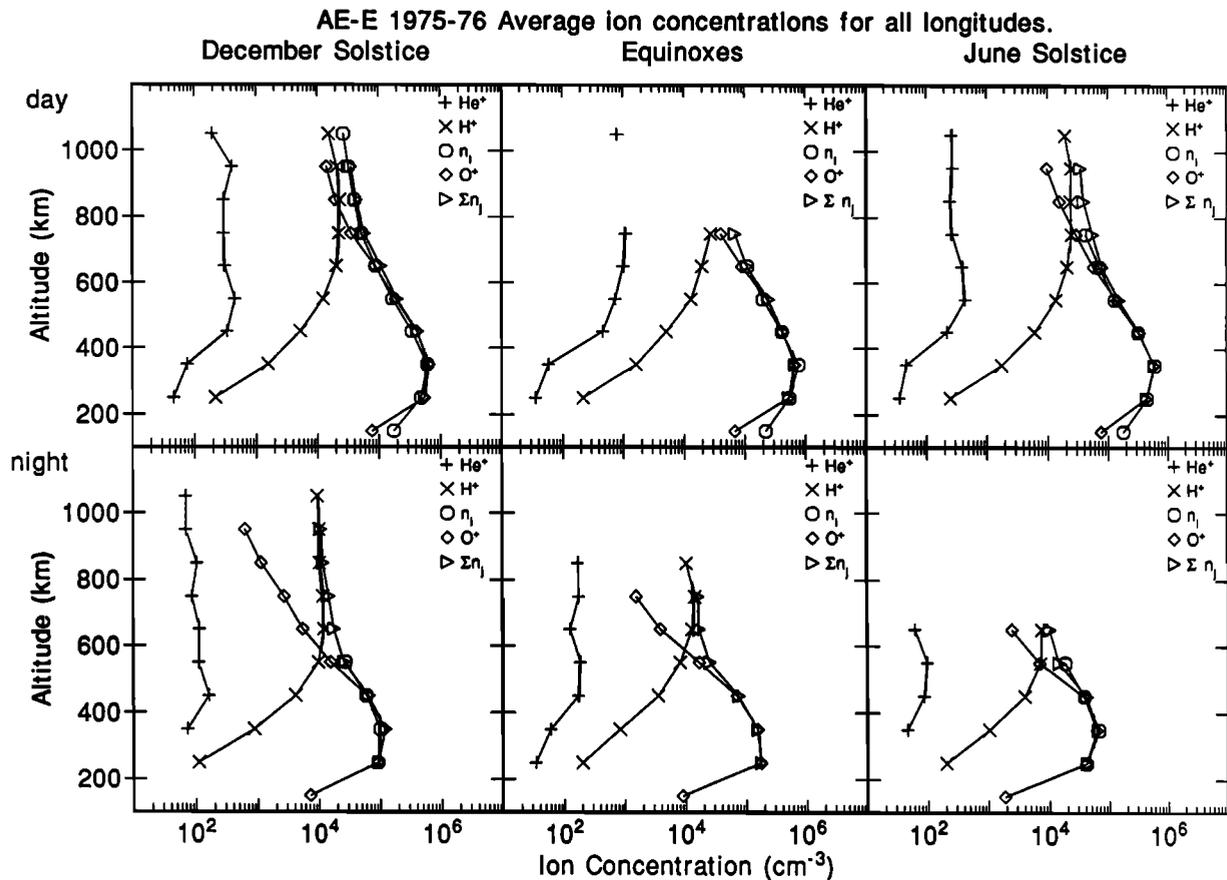


Fig. 3. Daytime (0800 to 1800 LT) and nighttime (2000 to 0500 LT) averages of $[O^+]$, $[H^+]$, and $[He^+]$ at different seasons. The average concentrations from the BIMS have been normalized by a factor of 2.15. The number of points in each 100-km bin is largest for O^+ and H^+ in the 300- to 600-km range. No average values are given when there are fewer than 12 samples.

that the average concentration above 400 km for both these seasons is between about 100 and 200 ions cm^{-3} .

DISCUSSION AND CONCLUSIONS

Data from the ion mass spectrometer on AE-E is sufficiently abundant that a statistical description of the major features of the topside equatorial ionosphere is possible. Inspection of the individual data shows that near the magnetic equator during the daytime, a combination of photoionization at lower and higher altitudes, along with an upward $E \times B$ drift, provides an essentially constant altitude for the F region peak. H^+ is produced primarily by the resonant charge exchange process between O^+ and neutral hydrogen. This reaction represents a sink for the topside O^+ , and the equilibrium concentrations produce an O^+/H^+ transition height near the H^+ peak. During the solar minimum conditions studied here, this height lies between 750 and 825 km. At night the O^+ concentration decays due to recombination at lower altitudes. The charge exchange reaction now reverses direction, with H^+ becoming a source for O^+ in the topside. The transition altitude falls to between 550 and 600 km, with the height of maximum $[H^+]$ varying between 600 and 800 km. The peak $[H^+]$ during the daytime is about $2.5 \times 10^4 cm^{-3}$ and at night is $10^4 cm^{-3}$ with little dependence on season seen at the dip equator. We emphasize that the observed concentrations show a variability of about a factor of 4; the mean values and any seasonal dependence in localized longitude sectors cannot be extracted with any significance from this data set. At a fixed altitude in the topside ionosphere one might expect larger O^+ and H^+

concentrations at the dip equator during solstice than during equinox, since interhemispheric transport, which is larger during solstices, tends to move plasma from the Appleton peaks closer to the dip equator. We suspect that the rather large dip latitude range over which the data are collected removes this signature from the average profiles by including not only the increase in density at the equator but also the decrease in the concentrations on the downwind side.

The O^+ peak concentration changes by about an order of magnitude from day to night, having a daytime value near $10^6 cm^{-3}$. During these solar minimum conditions the $E \times B$ drift velocity has an almost sinusoidal variation with local time, and the lack of significant postsunset enhancement means that the average daytime and nighttime F peak altitudes are about the same. In this study the F peak appears at about 350 km at all seasons.

He^+ is always a minor ion species at all altitudes in the topside equatorial ionosphere at solar minimum. The transport of He^+ will be dominated by the motion of O^+ , to which He^+ is collisionally bound, and thus a small seasonal variation similar to that seen in $[O^+]$ appears in the data. The He^+ peak concentration varies between 100-200 cm^{-3} during the night and about 400 cm^{-3} during the day except during the equinox, when it peaks at more than 1000 cm^{-3} during the day. Calculations by Murphy *et al.* [1984] show that interhemispheric transport during the solstices produces He^+ concentrations at the solstices that are lower than those at equinox by about a factor of 2. The observations are in accord with this result given that the rather broad bins used introduce a

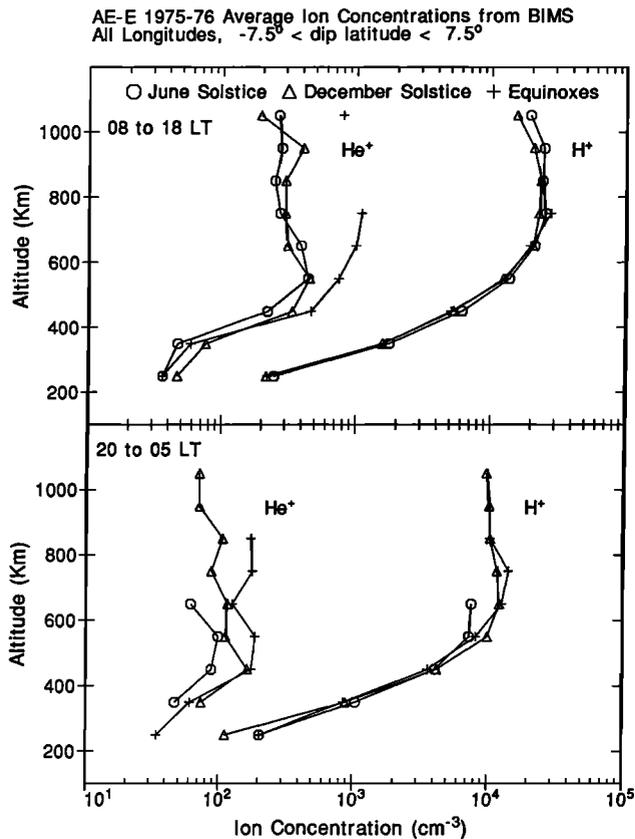


Fig. 4. Seasonal variation of the normalized concentrations of the light ions in the equatorial ionosphere during 1975-1976.

lot of variability. Although the results presented here are a good start in determining the distributions and variations of the major topside species at equatorial latitudes, clearly more data are needed to determine longitudinal effects and also to extend this study to higher latitudes. It should be emphasized again that considerable variability (a factor of 3) about the mean values can be attributed to daily changes in neutral wind and $E \times B$ drift patterns.

The concentrations from the BIMS and RPA from AE-E differ by a factor of about 2.15. The RPA data seem to be in good agreement with ground-based observations, while the concentrations from the BIMS are too low. The larger values for the ion concentrations suggested in this study might have significant impact on empirical models that were based on the AE-E mass spectrometer measurements.

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- B. G. Fejer and S. A. González, Center for Atmospheric and Space Sciences, Utah State University, Logan, UT 84322-4405.
- W. B. Hanson and R. A. Heelis, Center for Space Sciences, Physics Programs, University of Texas at Dallas, Richardson, TX 75083.

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