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IONOSPHERIC ION COMPOSITION FROM SATELLITE MEASUREMENTS MADE DURING 1970-1980: ALTITUDE PROFILES

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ABSTRACT

Ion mass spectrometers were carried by a number of satellites in the 1970s. The ion composition measurements from two of these missions, the Orbiting Geophysical Observatory-6 and the Atmosphere Explorer-C, have been collected into an ion composition data base to evaluate several widely used empirical and theoretical models for the species H^+, He^+, N^+, O^+, NO^+, $N_2{}^+$, and $O_2{}^+$. The data base covers all latitudes and local times, and the altitude range from 150 km to 1200 km, but here we present altitude plots of the ion densities at noon and at dip latitudes of 20-40^o N. The satellite data are compared with an early ion density profile by Johnson, with the Koehnlein and IRI-90 empirical models, and with the Utah State University theoretical ionosphere model. These comparisons serve to verify some aspects of the models, but they also reveal some outstanding differences. The solar activity dependence of H^+, He^+, N^+, and O^+ is demonstrated, although this has not been possible for the molecular ions because low altitude measurements have not been made near solar maximum.

INTRODUCTION

The importance of a knowledge of ion composition for understanding ionospheric plasma processes such as plasma outflow, the polar wind, ion chemistry, and a variety of plasma instabilities cannot be overstated. A series of satellites made in situ ion composition measurements between late the 1960s and the early 1980s. References to these satellites and the resulting data bases are given by Bilitza /1, 2/. Explorer 31 made ion composition measurements between 600 and 3600 km between November 1965 and January 1971. Additional ion mass spectrometer (IMS) measurements were made by Explorer 32 between May 1966 and March 1967, by OGO-6 between June 1969 and June 1971, by ISIS-2 between April 1971 and December 1972, by AE-C between December 1973 and December 1978, by S3-1 between November 1974 and May 1975, by TAIYO between February 1975 and May 1976, by AE-D between October 1975 and January 1976, by AE-E between November 1975 and June 1981, by S3-3 between July 1976 and March 1980, and by KYOKKO between February 1978 and November 1979. The only ion composition measurements during the 1980s were made between 800 and 900 km from IK1300 between August 1981 and December 1983 and from the AE-E at low latitudes and at altitudes in the vicinity of the F region peak.

Clearly, the 1970s provided a rich ion composition data base. These satellites covered a wide range of latitudes and altitudes, and the full range of local times were covered. Owing to the relatively short lifetimes of the satellites, however, the full range of solar cycle variations was not resolved, particularly for measurements in the lower F region which are only available from the deep diving AE satellites. A similar F region global data base is not available for the 1980's.

In this brief paper, altitude profiles of the ion composition measurements of the 7 species H^+, He^+, N^+, O^+, N_2^+, NO^+, and O_2^+ are constructed statistically from OGO-6 and AE-C ion measurements. AE-C was the first in a series of three Explorer satellites which were provided with propulsion to control perigee and apogee, thus making possible in situ measurements down to nearly 130 km. See Hoegy and Grebowsky /3/ for further details on the AE-C orbit. These data are compared with the latest International Reference Ionosphere, IRI-90, (Bilitza, private communication), the empirical Koehnlein model /4, 5/, and the Utah State University theoretical model of Schunk /6/. The data are also compared with the early altitude profile of Johnson /7/ which was the first calibrated profile of ion density using satellite and rocket data.

THE SATELLITES AND THE MODELS

Before comparing the OGO-6 and AE-C data with the empirical and theoretical models, we provide further information on the satellites and the models. The OGO-6 and AE-C ion mass spectrometers were nearly identical instruments, and the data were not normalized to any other measurements, so comparisons are expected to be especially meaningful. However, the two missions were conducted at quite different parts of the solar cycle, so we have an opportunity to examine the variation of ion composition with solar activity, at least at altitudes near and above the F2 peak.

The measurements used in the Johnson paper /7/ were made in early 1963 (rocket measurements from 90 km to 240 km) and early 1964 (satellite measurement 400 km to 1200 km). Thus the rocket and satellite data used by Johnson were not obtained simultaneously, and were not taken at the same local time or latitude. The rocket was launched at White Sands, New Mexico at 9:34 local time and 33° N latitude on February 15, 1963 while the the data from the Soviet satellite, Electron 2, covered the local time period 1400-1900 hrs over latitudes 10°-60° N latitude and at altitudes from 400 km to 1200 km during February 10-16, 1964. The ion composition measurements used by Johnson were converted to absolute ion densities by normalizing to electron densities obtained from simultaneous Doppler radio propagation and ionosonde measurements. This was a period of low solar activity, with the 3 month average 10.7 cm solar radio flux about 70 FU, similar to those present during most of the AE-C mission.

The OGO-6 data were obtained when the 3 month average 10.7 cm flux was about 140 FU. The OGO-6 data set covers the time period June 1969 to June 1971 in the altitude range 390 km to 1036 km. For the present comparisons, only data in the local time range of 2 hrs about noon and in the dip latitude range 20-40° N were selected, and data from all seasons are included. The data were uniformly distributed in longitude (UT) and occurred in a 20 day interval centered on day 130 and in a 30 day interval centered on day 215. These two intervals occur nearly symmetrically about summer solstice. The OGO-6 data were obtained from the NSSDC on IBM tapes which were converted from EBCDIC to ASCII format and stored on magnetic disk for data processing. The ASCII data were also written on magnetic tapes and returned to the NSSDC for archiving.

The lowest altitude AE-C data were obtained during the eccentric phase of that mission in 1974 when F10.7 was about 80 FU. In 1975 and 1976, when AE-C was in a circular orbit near the altitude of the F peak (about 300 km), the 10.7 cm flux was about 70. During 1977 and 1978 the orbit was maintained at about 400 km, and the 10.7 cm flux varied between 70 and 130, with an average of about 90 FU. Thus the lower altitude AE-C measurements represent the same solar minimum conditions as the early Johnson profiles. The circular orbit phase corresponded to more moderate solar activity. The AE-C data cover the time period from day 350 of 1973 to day 184 of 1978. The AE-C data used here covered the altitude range 150 km to 1200 km and were limited to local times of 2 hrs about noon and the dip latitude range of 20-40° N for all seasons. These data occurred in 3 intervals about 20 days long, centered at days 50, 130, and 255. Most of the data above 400 km occurred in the day 130 interval. The data are uniformly distributed in longitude. Thus at altitudes where the AE-C and OGO-6 data overlap, the two data sets have the same seasonal and longitude coverage. The AE-C data were obtained from the Unified Abstract file of 15 sec averages which is also available from the NSSDC

The IRI is a joint project of COSPAR and URSI which has evolved a series of empirical models of various parameters /8/, see references in /1/. The latest IRI model, IRI-90 /9/ contains an improved ion composition model that is based on the Danilov-Yaichnikov model /10/ which was derived from high apogee rockets and the satellites Electron 2 and 4, and S3-1. The IRI-86 ion composition model was based on data from 42 rockets below 200 km and the AEROS satellite measurements at higher altitudes. The IRI model contains ion composition for only the 5 species H^+, He^+, O^+, NO^+, and O_2^+ from which the ion densities are obtained by multiplying the composition by the electron density. IRI-90 model values were derived for altitudes from 100 km to 1200 km at noon local time and for a dip latitude of 30° N, for mid February and at a longitude of 106° W and low solar activity (70 FU) to match the conditions of the Johnson data. The longitude should not be important because the same dip latitudes were used as the data, however, the IRI model is dependent on longitude and in a small way on season (this will be discussed later).

The Koehnlein empirical model /4, 5/ is based on observation of AE-B, AE-C , AE-D, AE-E, ISIS-2, and OGO-6 satellites plus rocket data for quiet magnetic conditions $K_p \leq 3$. The model represents the 7 ion species H^+, He^+, N^+, O^+, N_2^+, NO^+, and O_2^+ and uses cubic splines to represent the vertical structure and employs harmonic functions for the horizontal dependence. The model is available only in the form of plots, therefore it is difficult to compare it under the same conditions as the other models and the OGO and AE data. We digitized the data from the Koehnlein plots of average density at low solar activity. The results should therefore compare well with the AE-C data plotted here.

The Utah State University (USU) theoretical model /6/ was used in a parameterized form provided by R. Daniell and D. Anderson (private communication) in which vector spherical harmonics were used to describe the model at high latitudes. Altitude profiles of O^+, NO^+, and O_2^+ were obtained between 100 km and 800 km for midday, summer conditions at low magnetic and solar activity, B_y positive, and 18 hrs UT. The model latitude selected was 51° Λ, since this is the lowest possible latitude covered by the model. This latitude is somewhat above the range of latitudes used for the comparison with other models and measurements, however, the comparison of general trends proved valuable.

COMPARISONS OF THE AE-C AND OGO-6 DATA WITH THE MODELS.

The altitude plots of the 7 selected species are shown in Figures 1-7. The points represent individual OGO-6 measurements, and the 15 sec averaged values from the AE-C measurements. The horizontal striations in the AE-C data are an artifact of the denser measurement coverage at the different circular orbit altitudes that were maintained at various times in the mission. Averages of the AE-C data over a 50 km altitude interval are represented by filled circles, while the averages of the OGO-6 data over 50 km are represented by 5-pointed stars. One sigma error bars are displayed. The solid lines represent the Johnson empirical model. Open circles represent the IRI-90 model; open triangles represent the Koehnlein model; and open squares represent the USU model.

H^+ Density

Figure 1 compares the H^+ densities from the satellites and the models. The AE-C data obtained during its eccentric phase extends down to about 230 km where the H^+ concentration fell below the spectrometer threshold. The error bars on the AE-C and OGO-6 average profiles indicate one standard deviation of the log of the densities within each 50 km interval. The OGO and AE data differ in important respects, with the AE-C values significantly higher between 500 and 900 km. The AE-C H^+ density is a factor of 6.5 greater than the OGO-6 density at 600 km. This difference could be due to differences in solar activity, a different seasonal bias of the data sets, or a longitudinal bias of the data sets. As mentioned above, there is no longitudinal bias in the OGO-6 and AE-C coverage. The seasons are nearly the same where the data overlap in altitude, since most of the OGO data above 600 km were taken midway between summer and fall, while the AE-C data were obtained midway between spring and summer. Therefore we conclude that the H$^+$ density differences in the OGO-6 and AE-C data are due to solar activity. This comparison shows that H$^+$ decreases with increasing solar activity.

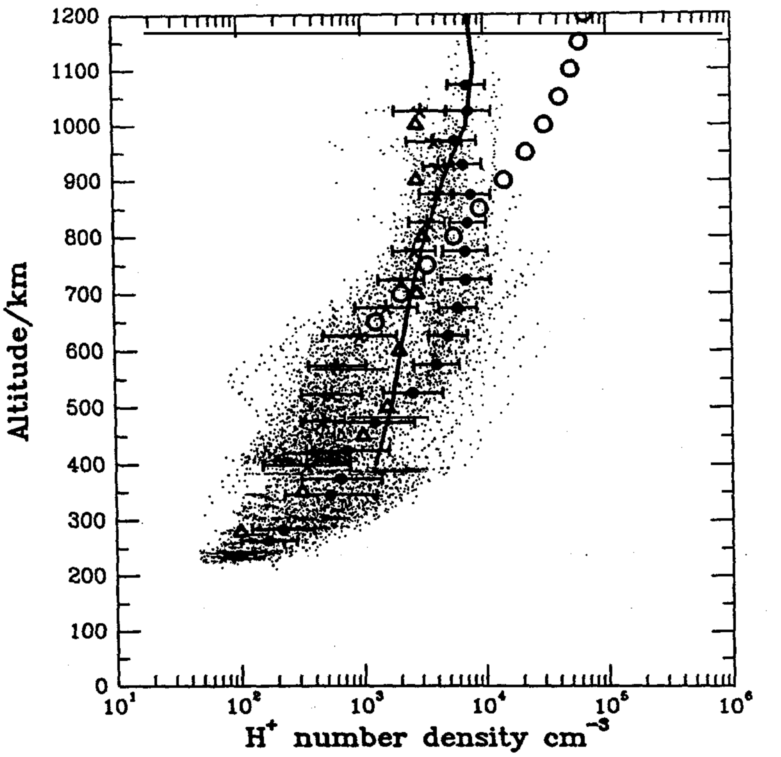

Fig. 1. Comparison of satellite data from AE-C and OGO-6 (points) for dip latitudes 20 to 40 and LST 10 to 14 with models for H$^+$. Johnson model (solid line), AE-C average over 50 km (solid circle), OGO-5 average over 50 km (5 pointed star), IRI-90 model (open circle), and Koehnlein model (triangle). Altitude in km and number density in cm^{-3}.

The Johnson profile falls generally between the AE-C and OGO-6 measurements, except below 500 km where it exceeds both of the satellite average profiles. The density gradient of the Johnson profile is rather flat compared with the data. The IRI-90 model H$^+$ profile is steeper than the satellite profiles, but it diverges above 800 km and is an order of magnitude greater than the AE-C values at 1200 km. The IRI model extends only down to 650 km because ion composition less than 1% is neglected. The Koehnlein model agrees with the AE-C data below 500 km and tends to follow the OGO-6 data above 700 km, although it should agree only with the low solar activity AE-C data.

A number of factors could contribute to the difference between the satellite and model profiles of H$^+$. Longitude variation of the IRI model introduce a spread of about a factor of 4 in the density. The seasonal variation of IRI introduces about a 37% variation at 700 km, with winter having the highest density and summer the lowest. The Koehnlein seasonal variation of H$^+$ is opposite to the IRI-90 variation. The width of the AE-C and OGO-6 bins (20^o in latitude, 4 hrs in local time, all longitudes allowed, all magnetic activity allowed) contributes to the scatter in the satellite data.

He$^+$ Density

Figure 2 compares the He$^+$ densities from the satellites and the models. The AE-C and OGO-6 data and the Johnson profiles show nearly constant density between 600 km and 900 km, with the satellite data about a factor of 3 lower. The AE-C values rise well above the OGO-6 measurements below 600 km where they agree better with the Johnson model. This behavior is consistent with solar activity biases in the data bases; at low altitudes He^+ decreases with increasing solar activity; at high altitudes it has the opposite behavior. The arguments used to rule out longitude and seasonal causes for differences in OGO-6 and AE-C measurements of H^+also apply to He^+. The IRI-90 profile diverges radically from the data above 600 km. Below 800 km, the Koehnlein profile lies between the OGO-6 and AE-C averages. This behavior is not understood, since the Koehnlein profile is for low solar activity. Above 600 km, the Koehnlein profile agrees well with the both the AE-C and OGO-6 data.

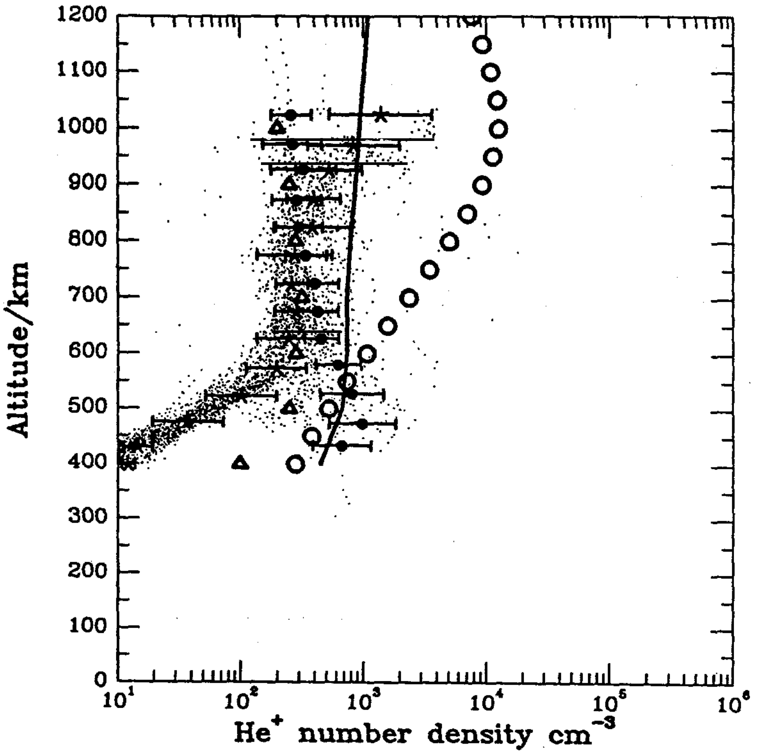

Fig. 2. Comparison of satellite data from AE-C and OGO-6 with Johnson, IRI, and Koehnlein models for He^+. Same symbols as Fig. 1.

N^+ Density

Figure 3 compares the N^+ densities from the satellites and the models. They agree well, except for the Koehnlein model. The Koehnlein model is consistently lower than the AE-C data and falls off faster than the data at the highest altitudes, although it has the same slope as the OGO-6 data above 400 km. The differences between the OGO and AE measurements suggest a solar activity variation, with the N^+ density increasing with increasing activity. This behavior is opposite that of the lighter ions in this altitude range. The Johnson profile agrees well with the OGO-6 and AE-C averages.

O^+ Density

Figure 4 compares the O^+ densities from the satellites and the models. The OGO-6 and AE-C

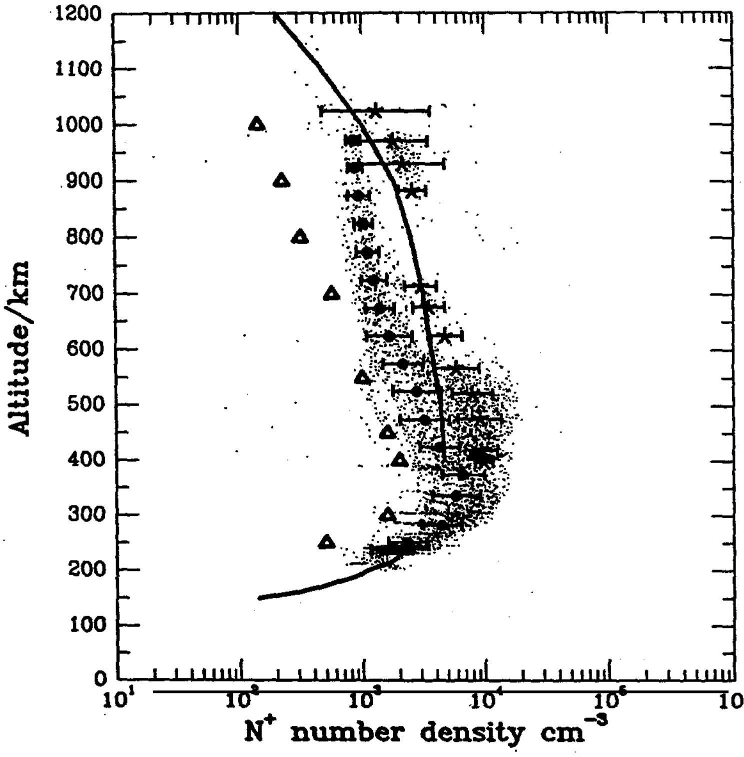

Fig. 3. Comparison of satellite data from AE-C and OGO-6 with Johnson and Koehnlein models for N$^+$. Same symbols as Fig. 1.

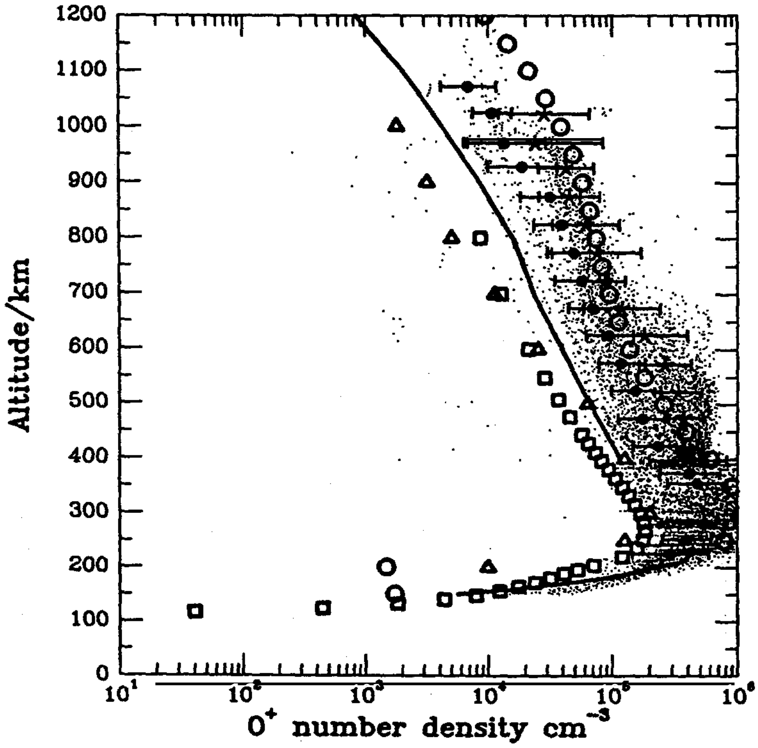

Fig. 4. Comparison of satellite data from AE-C and OGO-6 with Johnson, IRI, Koehnlein empirical models and USU theoretical model (square) for O$^+$. Same symbols as Fig. 1.

measurement reveal a small solar activity effect similar to that of N^+, with the density increasing with increasing solar activity. The Johnson profile is consistently lower than the satellite data by about a factor of 4. The IRI-90 model agrees rather well with the OGO-6 data, and is higher than the AE-C data except at altitudes below the F2 peak. The Koehnlein model falls about a factor of 4 below the AE-C data, but the profile has nearly the same shape. The shape of the USU model is also similar, but it falls below the data because the model corresponds to dip latitude of 55° rather than 20-40 degrees for the other profiles. If the behavior of the IRI model as a function of dip latitude is used to scale the USU model to 30° dip latitude, then the USU model lies within the error bars of the AE-C data.

N_2^+ Density

Figure 5 compares the N_2^+ densities from the satellites and the models. The AE-C and OGO-6 data agree at 400 km, but the error bars on the OGO-6 averages are so large that the increase in N_2^+ above 400 km cannot be trusted. There may be some increase in N_2^+ with increasing solar activity, but probably not enough to produce the observed difference in the averages of AE-C and OGO-6. The AE-C data appear to be consistent with the Johnson profile at 250 km. The Koehnlein model also agrees with the AE-C data between 250 km and 400 km, but exhibits a lower peak density than either the AE-C data or the Johnson profile.

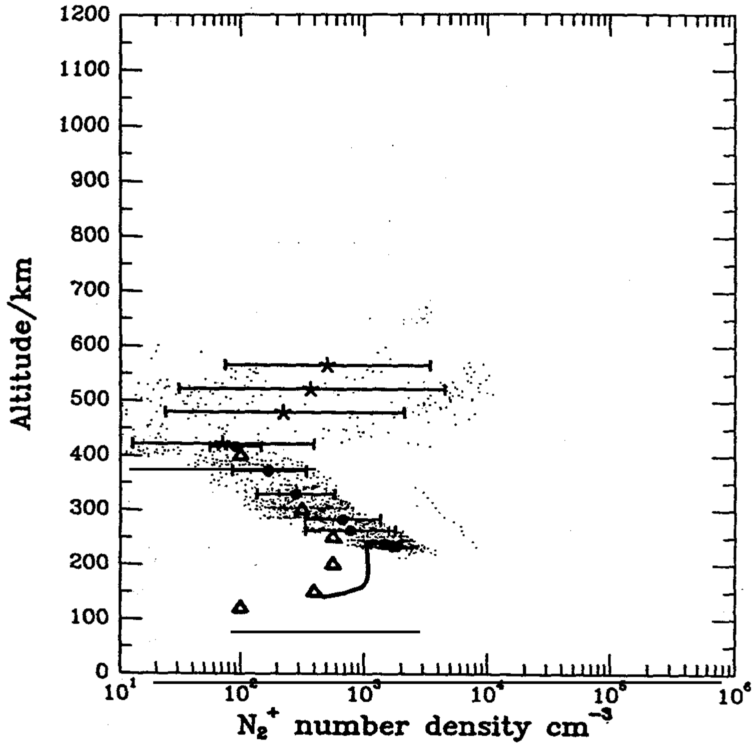

Fig. 5. Comparison of satellite data from AE-C and OGO-6 with Johnson and Koehnlein models for N_2^+. Same symbols as Fig. 1.

NO^+ Density

Figure 6 compares the NO^+ satellite measurements and the models. OGO-6 data are too sparse to place much credence in the differences evident above 400 km. The Johnson profile is consistent with the AE-C data at 225 km where they overlap. The IRI-90 model agrees with the AE-C data above 250 km. Below this altitude, IRI-90 exhibits a bite-out at about 190 km and a density increase at low altitude which is inconsistent with the Johnson and the USU profiles. The Koehnlein model exhibits a lower peak density at about 150 km than the other profiles, but is consistent with the AE-C data above 200 km. The USU model agrees with the Johnson profile below the peak height and agrees with the AE-C data and IRI-90 above 200 km. The IRI-90 model indicates little latitude variation of the NO^+ density above 200 km, therefore the USU model at 55° dip latitude should agree with the data and IRI model at 30° dip latitude, which it does. The two layer structure of the IRI-90 model at 30° dip latitude disappears at 55° dip latitude.

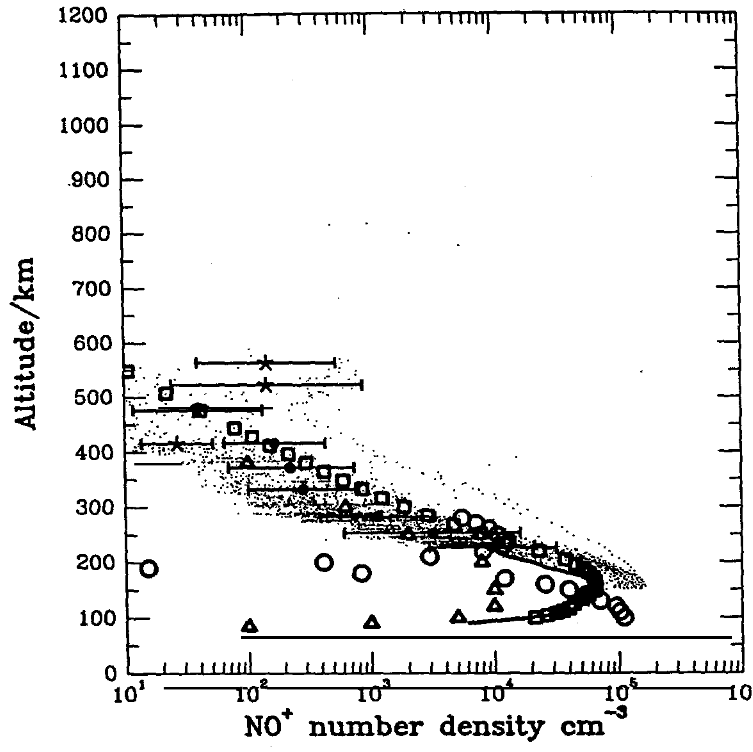

Fig. 6. Comparison of satellite data from AE-C and OGO-6 with models for NO^+. Same symbols as Fig. 4.

O_2^+ Density

Figure 7 compares the O_2^+ densities from the satellites and the models. The AE-C and OGO-6 densities agree very well up to about 400 km, where a few outlier points cause the AE-C average to diverge from the general trend. The Johnson profile matches the AE-C trend where they overlap between 150 and 210 km. The IRI-90 profile is slightly higher than AE-C at altitudes above 250 km, and is lower than the Johnson profile at lower altitudes. The Koehnlein profile agrees with the AE-C data above 250 km and exhibits a two layer structure at lower altitudes as does the IRI-90 profile. The USU profile is consistent with the AE-C data above the F peak.

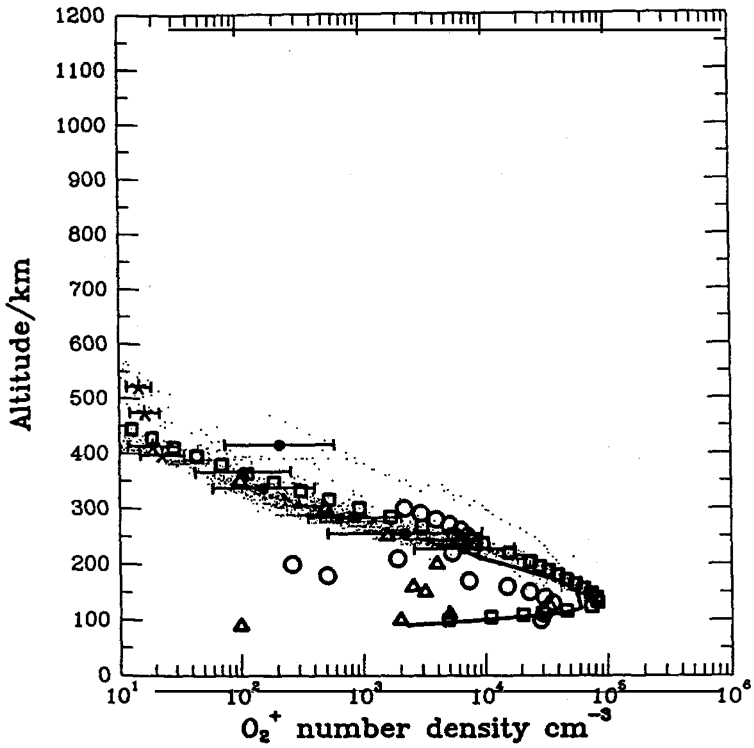

Fig. 7. Comparison of satellite data from AE-C and OGO-6 with models for O_2^+. Same symbols as Fig. 4.

CONCLUSIONS

The 7 ions H^+, He^+, N^+, O^+, N_2^+, NO^+, and O_2^+ measured by AE-C during solar minimum and by OGO-6 during a rather weak solar maximum have been displayed as altitude plots and compared with early altitude profiles of Johnson, with the IRI-90 and Koehnlein empirical models, and with the USU theoretical model. The satellite data indicate that the Johnson profiles are reasonable representations of the ion density, differing at the most by about a factor of 3. The Johnson profiles are systematically higher than the AE and OGO satellite measurements for He^+ and N^+ and are lower for O^+. The Koehnlein model at low solar activity should agree with the AE-C data, however, it sometimes agrees better with the OGO measurements, and it is systematically lower for N^+ and O^+. If the Koehnlein model were available in computer form, additional comparisons with the AE-C and OGO-6 data could be made more readily. The IRI-90 model does not agree well with the satellite data for H^+ and He^+, and its values for O^+ are about a factor of 2 higher than the AE-C averages. For NO^+ and O_2^+ above 250 km, the IRI-90 is higher than the satellite data. The USU model, when corrected for the latitude differences, agrees within a factor of 2 with the AE-C data. A better comparison with the USU model will be possible in the future when that model is available at lower latitudes.

We determined the variation of ion composition with solar activity. H^+ and He^+ decrease with increasing with solar activity, whereas N^+, O^+ increase. Since the OGO data exist only above 390 km, the variation of the molecular ions, N_2^+, NO^+, O_2^+, cannot be determined from this data base. More low altitude data are needed at higher solar activity levels.

These comparisons of the AE-C and OGO-6 ion composition measurements with the most widely used empirical and theoretical models have revealed a number of shortcomings in our understanding of some of the fundamental aspects of ionosphere behavior, particularly the variations in ion composition with solar activity. They demonstrate the need for further verification and upgrading of the models using existing spacecraft data, and the need for additional in situ measurements from deep diving satellites, particularly near solar maximum.

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