

Variation of F-Region Positive Ion Density with Solar Activity

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Rates of production of positive ions N_2^+ , N^+ , O^+ , O_2^+ and NO^+ by photoionization and other chemical reactions have been calculated in the altitude range 120-400 km for three different levels of solar activity. These levels of solar activity are characterized by three representative values of solar radio wave flux at 10.7 cm (2800 MHz) as 75, 175 and 275 $W/m^2 Hz^{-1}$ respectively, covering the entire range of observed values. Variations of the flux of the solar extreme ultraviolet radiation incident upon the atmosphere, neutral particle densities, electron density and temperature, with solar activity have been taken into account. Equilibrium concentrations of all the ionic species have been calculated using laboratory measured values of the rate coefficients of ion-neutral reactions. Computed ion density profiles have been compared with the observed data.

1. Introduction

MANY atmospheric parameters change during the course of a solar cycle. Due to the heat of the upper atmosphere by solar EUV radiation¹, the neutral particle density and the temperature of the ionosphere change with the solar activity². Again, a comparison of the electron density profiles obtained near solar maximum³ and those obtained near the minimum⁴ shows that at F_2 -peak, the electron density varies by a factor of about 5 (peak electron density near solar maximum is approximately $2.5 \times 10^6 cm^{-3}$ and $5.0 \times 10^5 cm^{-3}$ near the minimum). Lootens and Prenatt⁵ derived electron density profiles from data obtained in 1958 and 1964 which are representative profiles for solar maximum and minimum respectively. They also showed that the peak electron density near solar maximum is nearly 5 times higher than that at solar minimum.

The early measurements of positive ion densities of the ionosphere^{6,7} are meagre. These workers reported the relative concentrations of the major atmospheric ions, O^+ , O_2^+ and NO^+ only. Recently, Holmes *et al.*⁸ and Brinton *et al.*⁹ reported absolute density profiles of important positive ions. These measurements, however, do not span a full increasing or decreasing phase of the solar cycle.

The purpose of this investigation is to present a comprehensive account of the variations of positive ion densities with the solar activity.

2. Variation of Factors Affecting Positive Ion Densities with Solar Activity

2.1 EUV Fluxes

A summary of the data available for solar flux variations with the activity of the sun is given in Table 1. A variation by a factor of six for solar EUV flux has been obtained by Anderson^{10,11} from a consideration of atmospheric density variations. The results obtained by Hall *et al.*¹² indicate a variation for certain lines in this region by a factor of around 2 and for iron lines by a factor up to 10. Since

Anderson's computations^{10,11} consider both lines and continuum as against the discrete lines considered by Hall *et al.*¹², the EUV flux variation by a factor of 6 over a solar cycle has been adopted for calculation of positive ion densities.

2.2 Atmospheric Density

Variation of upper atmospheric densities with the solar activity is now well established². However, theoretical models derived from a linear correlation between the solar EUV and 10.7 cm flux exhibit deviations from the observed models¹³.

TABLE 1 — SOLAR FLUX VARIATION WITH THE ACTIVITY OF THE SUN

Source	Inference
NRC, Canada, quoted in CIRA (1965)	Since 1947, radio wave flux at 10.7 cm is measured continuously. A variation by a factor of 4 is observed from minimum to maximum. If a linear correlation between EUV and radio wave fluxes exists, the former should also change by a factor of 4
Anderson ^{10,11}	The upper atmospheric density variations from solar minimum to maximum as measured by satellite drag experiments show that the EUV flux varies by a factor of 6
Nicolet and Swider ¹⁴	From theoretical analysis, it has been concluded that the solar radiations responsible for F-region ionization should vary approximately fourfold from the minimum to maximum activity
Hall <i>et al.</i> ¹²	Measurements of solar EUV flux carried out by rocket-borne monochromator indicate a variation by a factor varying from 1.5 to 2.3. For Fe lines, however, variation up to a factor of 10 is observed

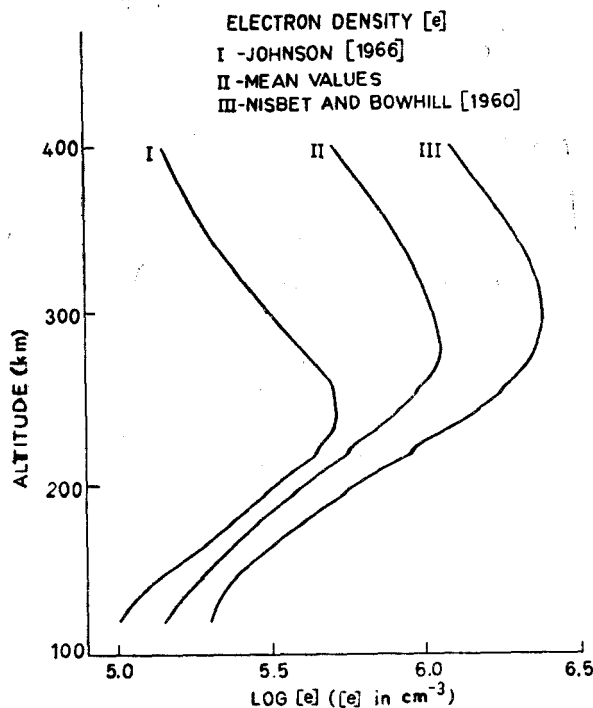


Fig. 1 — Electron density profile for the three levels of solar activity

Atmospheric models used in COSPAR International Reference Atmosphere (CIRA) (1965) are based on the assumption of a linear correlation. Models 2, 6 and 10 of CIRA (1965) have been adopted for low, medium and high levels of solar activity.

2.3 Electron Density

Fig. 1 shows the electron density profiles used in the calculations for the three models. The low activity profile I has been adopted from Johnson¹⁵ which is the average of many measurements carried out during minimum solar activity. The high activity profile III has been deduced from the data obtained by Nisbet and Bowhill³. These workers carried out several measurements of electron density distributions during the solar maximum condition (1958-59). The adopted profile is the average of these data. The medium activity profile II is derived from many different sources, obtained during the period between minimum and maximum solar activity.

3. Photochemistry of F-Region

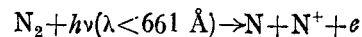
To obtain the positive ion densities in the F-region, it is necessary to consider the following processes:

- (i) photoionization of neutral atmospheric constituents by solar EUV radiations,
- (ii) charge-transfer and ion-atom interchange (jointly called ion-neutral reactions),
- (iii) dissociative recombination of molecular ions with electrons, and
- (iv) ambipolar diffusion of electron-ion plasma.

Of these, processes (i), (ii) and (iii) control primarily the distributions of positive ions. If, however, the photochemical lifetime of an ion is large, ambipolar diffusion will play an important role¹⁶. Computations show that below the F_2 -peak, the distribution of ionization is essentially photochemical, while above it is diffusive¹⁷.

3.1 Photoionization

O^+ , O_2^+ and N_2^+ ions are produced directly by photoionization of their neutral species. McElroy¹⁸ has shown that the production of N^+ in the ionosphere takes place by the dissociative photoionization of N_2 through the reaction



with an efficiency of about 21% NO^+ is produced entirely by ion-neutral reactions and, therefore, its photoionization will not be considered.

Ion production rates by photoionization have been calculated following the procedure outlined by Watanabe and Hinteregger¹⁹. Solar flux values reported by Hinteregger *et al.*²⁰ have been adopted for the low activity model, and those appropriate for medium and high activity models are obtained by multiplying the low activity values by 2.5 and 6 respectively. Neutral particle and temperature distributions for the three models have been adopted from models 2, 6 and 10 of CIRA (1965). Photoionization and absorption cross-sections have also been taken from Hinteregger *et al.*²⁰. Ion production rates for the three levels of solar activity are shown in Figs. 2, 3 and 4 respectively. It may be noted that the calculated low activity photoionization rates are in good agreement with those obtained by Hinteregger *et al.*²⁰ which refer to low activity conditions.

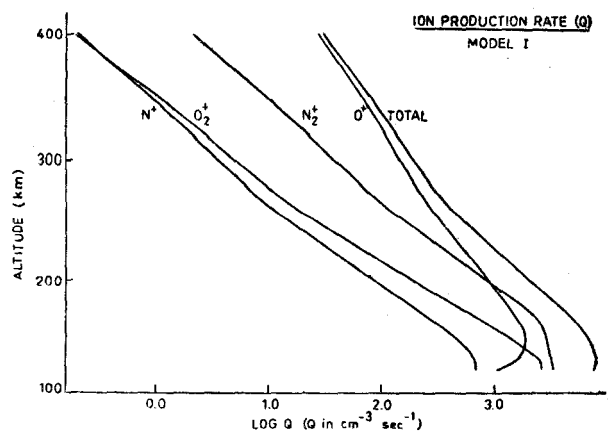


Fig. 2 — Photoionization rates of atmospheric constituents for low level of solar activity

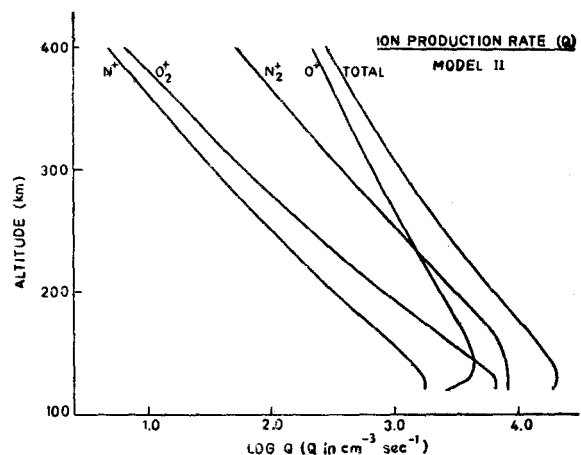


Fig. 3 — Photoionization rates of atmospheric constituents for medium level of solar activity

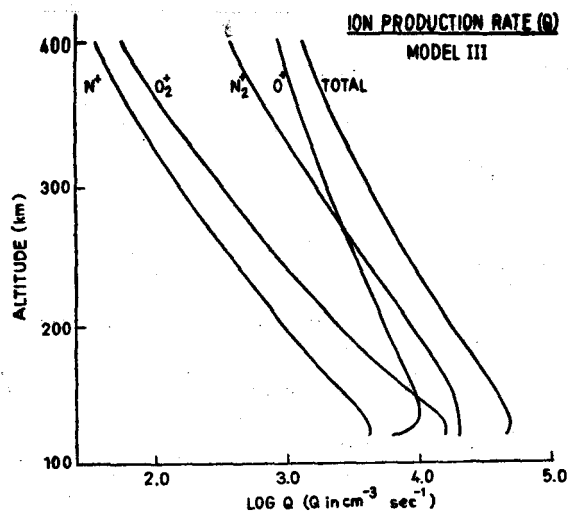


Fig. 4—Photoionization rates of atmospheric constituents for high level of solar activity

3.2 Ion-Neutral and Dissociative Recombination Reaction

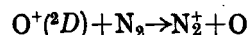
Ion-neutral and dissociative recombination reactions which are of importance to F-region photochemistry are critically reviewed in Table 2.

4. Variation of Positive Ion Density with Solar Activity

Considering the various production and loss processes, the variations of all positive ion densities are obtained and discussed separately.

4.1 N^+ Ions

N_2^+ ions in the daytime ionosphere are produced mainly by photoionization of N_2 . Computations show that N_2^+ ions, produced by the charge-transfer reaction between metastable O^+ ions and N_2 , namely



make a minor contribution.

TABLE 2—REACTIONS CONTROLLING F-REGION IONIZATION

Sl No.	Reaction	Rate coeff. (cm ³ sec ⁻¹)	Ref.	Method used for obtaining rate coeff.†	Adopted rate coeff.† (cm ³ sec ⁻¹)	Remarks
ION-NEUTRAL REACTIONS						
1.	$O^+ + O_2 \rightarrow O_2^+ + O^*$	4.0 (–11) 2.0 (–11) 2.0 (–11) 4.0 (–11)	24 26 27 23	A B C D	3.0 (–11)	Rate coefficients measured by different techniques agree within a factor of two. Adopted value is the average of measured values. Due to high rate coefficient and large O_2 concentration, this reaction contributes appreciably to the loss of O^+ and also the production of O_2^+ in the altitude range 120–400 km
2.	$O^+ + N_2 \rightarrow NO^+ + N^*$	3.0 (–12) 4.7 (–12) 2.4 (–12) 4.6 (–12) 1.8 (–12)	25 28 26 27 29	A B B C A	3.0 (–12)	Different measurements agree well. Average value is adopted. Effect of vibrational excitation of N_2 on the rate coefficient is not ordinarily important. It may be important during magnetic storms and auroras ²¹ . Due to large N_2 concentration, this reaction makes significant contribution both to the loss of O^+ and production of NO^+ in the altitude range 120–400 km
3.	$O^+ + NO \rightarrow NO^+ + O$	2.4 (–11)	30	A	2.4 (–11)	Unimportant, rate of NO^+ production is small because of low concentration of NO
4.	$O_2^+ + N_2 \rightarrow NO^+ + NO$	<1.0 (–15) <1.0 (–15)	31 27	A C	1.0 (–15)	Rate coefficient is very low because the reaction involves the breakage of two bonds. Contributions both to the loss of O_2^+ and production of NO^+ are inappreciable
5.	$O_2^+ + N \rightarrow NO^+ + O$	1.8 (–10)	30	A	1.8 (–10)	In the altitude range (120–220 km), the concentration of N atom is large enough to make this reaction important. Unimportant at higher altitudes
6.	$O_2^+ + NO \rightarrow NO^+ + O_2$	8.0 (–10) 7.7 (–10)	30 27	A C	8.0 (–10)	In the altitude range (120–220 km), the concentration of NO is sufficient to make this reaction significant. Unimportant at higher altitudes
7.	$N_2^+ + O_2 \rightarrow O_2^+ + N_2^*$	1.0 (–10) 2.0 (–10) 1.1 (–10) 2.0 (–10)	25 32 27 23	A B C D	2.0 (–10)	Because of high rate coefficient and large O_2 concentration, this reaction is important. Adopted value, which is the highest of the available values, is supported by theoretical analysis. N_2^+ concentration is not very sensitive to the rate coefficient variation

TABLE 2 — REACTIONS CONTROLLING F-REGION IONIZATION — *Contd*

Sl No.	Reaction	Rate coeff. (cm ⁻³ sec ⁻¹)	Ref.	Method used for obtaining rate coeff.†	Adopted rate coeff.‡ (cm ⁻³ sec ⁻¹)	Remarks
ION-NEUTRAL REACTIONS — <i>contd</i>						
8.	$N_2^+ + O_2 \rightarrow NO^+ + NO$	<2.0 (-13) 2.0 (-13)	33 24	F A	2.0 (-12)	The rate coefficient is low because it involves breakage of two bonds. The reaction makes inappreciable contribution
9.	$N_2^+ + O \rightarrow NO^+ + N^*$	2.5 (-10) 2.0 (-10)	34 23	A D	2.5 (-10)	Because of the high rate coefficient and large O concentration, the reaction is important in the entire altitude range (120-400 km) both for the loss of N_2^+ and production of NO^+
10.	$N_2^+ + O \rightarrow O^+ + N_2$	<1.0 (-11) 6.0 (-12)	34 23	A D	6.0 (-12)	Rate coefficient is low. Unimportant for the loss of N_2^+ compared to reaction 9 and for the production of O^+ compared to direct photoionization
11.	$N_2^+ + N \rightarrow N^+ + N_2$	<1.0 (-12)	16	D	1.0 (-12)	The reaction makes insignificant contribution because of low rate coefficient and small N atom concentration
12.	$N_2^+ + NO \rightarrow NO^+ + N_2$	5.0 (-10) 4.8 (-10)	30 35	A C	5.0 (-10)	Despite the high rate coefficient, its contribution is insignificant as NO concentration is low
13.	$N^+ + O_2 \rightarrow O_2^+ + N^*$	1.0 (-09) 7.0 (-10)	25 36	A F	5.0 (-10)	For the loss of N^+ ion, the two reactions are considered jointly. The average value is adopted. With this value the agreement of N ion distribution with the observed data is good
14.	$N^+ + O_2 \rightarrow NO^+ + O^*$	6.5 (-10) 2.5 (-10) 5.0 (-10)	27 18 23	C D D		
15.	$N^+ + NO \rightarrow NO^+ + N$	8.0 (-10)	30	A	8.0 (-10)	Despite the high rate coefficient this reaction is unimportant because of very low NO concentration
DISSOCIATIVE RECOMBINATION REACTIONS						
16.	$O_2^+ + e \rightarrow O + O$	1.7 (-07)	22	E	1.7 (-07)	Important throughout the 120-400 km range. Dominant at altitudes above 220 km
17.	$N_2^+ + e \rightarrow N + N^*$	2.8 (-07)	22	E	2.8 (-07)	Below 220 km, unimportant compared to reactions 7 and 9. Above 220 km its contribution is appreciable due to high electron density in the F ₂ -region
18.	$NO^+ + e \rightarrow N + O^*$	5.0 (-07) 5.2 (-07)	22 23	E D	5.0 (-07)	This is the only loss process of NO^+ . The high value is obtained experimentally by Biondi ²² . This is also supported by Donahue ²³ because it yields NO^+ densities in better agreement with the observed data

*Rate coefficients for these reactions are temperature dependent. Donahue²³ concluded that these coefficients vary inversely with temperature. To obtain their values at T °K, the values obtained at 300°K are multiplied by $(300/T)$.

†In col. 5, the details of the method used are as follows: A, flowing afterglow; B, transient discharge; C, photo-ionization mass spectrometer; D, theoretical estimate; E, electron density decay; and F, electron-impact ionization mass spectrometer.

‡Raise 10 by the power given in parentheses and then multiply the result by the number preceding the bracket, e.g. the entry 3.0 (-11) means that the rate coefficient is 3.0×10^{-11} .

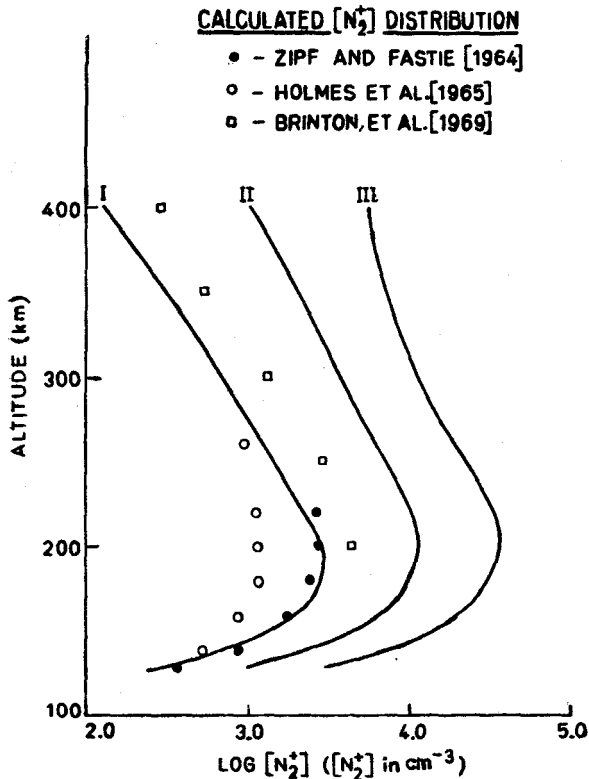


Fig. 5 — Computed N_2^+ profiles for the three levels of solar activity and the observed data

Significant loss of N_2^+ occurs through reactions 7, 9 and 17 (see Table 2, col. 1). It is to be noted that the calculated photochemical lifetime of N_2^+ at 400 km is 40 sec, and hence diffusive processes are not likely to affect the distribution of this ion. Computed density profiles of N_2^+ for the three levels of solar activity are shown in Fig. 5.

Data of N_2^+ ion density represented by solid circles were obtained by Zipf and Fastie³⁷ from the profile of emission rates of 3914 Å radiation of N_2^+ in the day airglow obtained from a rocket-borne experiment in 1963. It will be seen that these data agree well with the calculated values. The data of Holmes *et al.*⁸ are lower than the computed values around 200 km. This is due to the fact that while the computations refer to the noontime condition (solar zenith angle = 0°), the measurement was carried out in the afternoon when solar zenith angle $\approx 60^\circ$. Hence, the photoionization rate and the temperature-dependent rate coefficients are not the same for the two conditions. The data of Brinton *et al.*⁹ are systematically higher than the calculated low activity profile but lower than the medium activity profile. It may be noted in this connection that the measurements were carried out in 1966 when the level of solar activity was a little higher than the minimum.

4.2 N^+ Ions

N^+ ions in the daytime F-region are produced mainly by the dissociative photoionization of N_2 (ref. 18). Contribution of direct photoionization of N and charge-transfer reaction 11 (Table 2) have been found to be insignificant. Loss of N^+ occurs mainly through reactions 13 and 14. N^+ density profiles computed for the three levels of solar activity are

shown in Fig. 6. Since the photochemical lifetime of this ion at 400 km for the low activity model is approximately 40 min, the diffusive effects are expected to modify the distribution only slightly.

The low activity profile is in good agreement with the data reported by Johnson¹⁵. The profile obtained by Brinton *et al.*⁹ has a peak around 260 km, whereas no such peak is exhibited by Johnson's data. This may be due to the fact that Johnson's data are the average of several observations and for the calculated curves, diffusion is neglected.

4.3 O^+ Ions

O^+ ions in the daytime ionosphere are produced mainly by the photoionization of O. Contribution by the charge transfer reaction 10 is insignificant compared to the former. Chemical loss of this ion occurs mainly through reactions 1 and 2. However, the photochemical lifetime of this ion at high altitudes is very large and, therefore, its distribution is diffusive. Rishbeth and Barron¹⁷ have shown that peak density of an ion occurs at an altitude where the photochemical and diffusive lifetime become equal (diffusive lifetime = H^2/D , where D is the ambipolar diffusion coefficient for the O^+-e plasma and H is the atomic oxygen scale height). We have adopted the value of D calculated by Dalgarno³⁸ in the present calculation.

Photochemical loss rate $k_1 O_2 + k_2 N_2$ (where k_1 and k_2 are the rate coefficients of reactions 1 and 2 respectively) denoted for brevity by β and the diffusive loss rate D/H^2 have been plotted on the same graph against altitude. The altitude of intersection of these curves determines the position of the F_2 -peak. Fig. 7 shows the β and D/H^2 curves for low, medium and high levels of solar activity, and it is clear that the peaks of O^+ distribution occur around 250, 280 and 310 km respectively for the

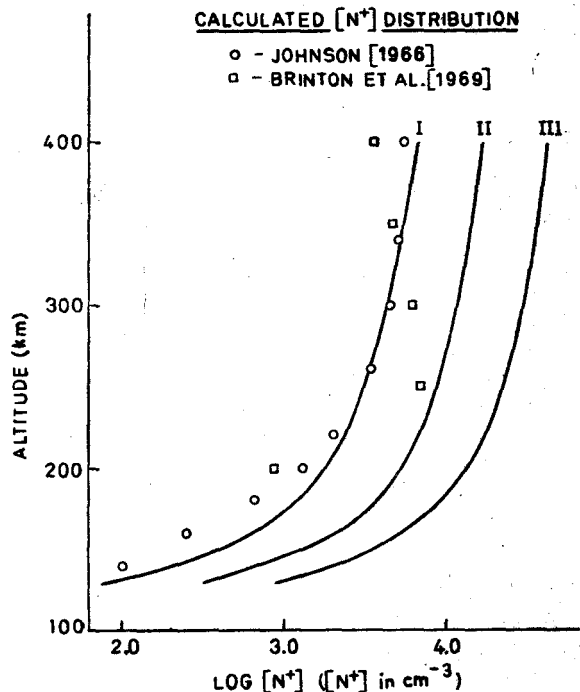


Fig. 6 — Computed N^+ profiles for the three levels of solar activity and the observed data

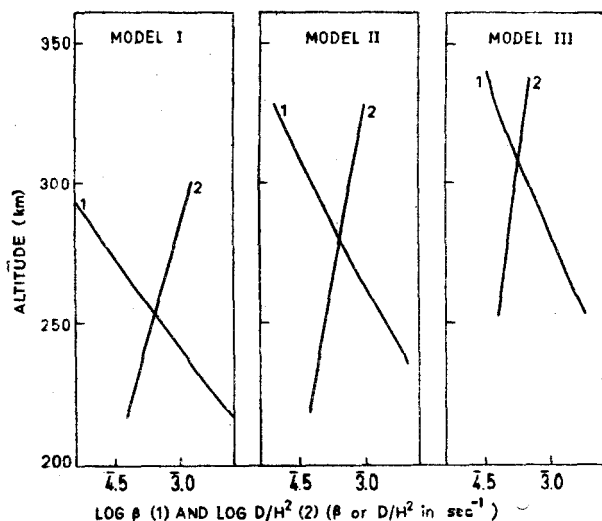


Fig. 7—Altitudes of F₂-peaks for the three levels of solar activity [Models I, II and III correspond to low, medium and high level of activity respectively]

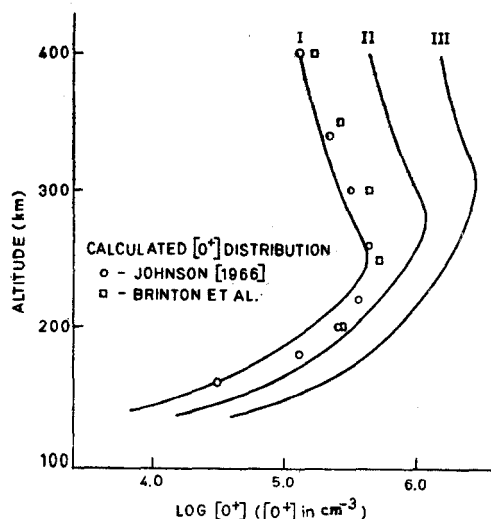


Fig. 8—Computed O⁺ profiles for the three levels of solar activity and the observed data

three models. Below these altitudes, the O⁺ densities are calculated by the photochemical formula, while above these peaks the calculation is made using the usual barometric formula. Fig. 8 shows O⁺ densities for the three models. The agreement between the computed profile for the low activity and the data of Johnson¹⁵ is good. Results of Brinton *et al.*⁹ are slightly higher than the low activity profile as expected but follow the same pattern of distribution.

A comparison of the adopted electron density profiles and the computed O⁺ profiles shows that above 200 km, the corresponding profiles agree with each other. This is due to the fact that O⁺ is the dominant ion in the daytime ionosphere above 200 km.

4.4 O₂⁺ Ions

O₂⁺ ions are produced by the photoionization of O₂, and also in appreciable quantity by chemical reactions 1, 7 and 13. Important loss processes are reactions 5, 6 and 16. The photochemical lifetime of this ion at 400 km is less than 1 min implying that the diffusive effects are negligible and

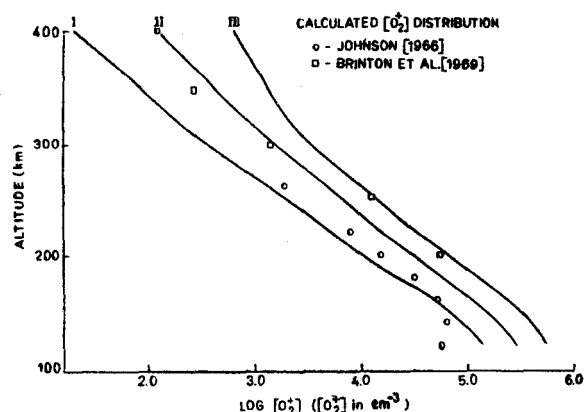


Fig. 9—Computed O₂⁺ profiles for the three levels of solar activity and the observed data

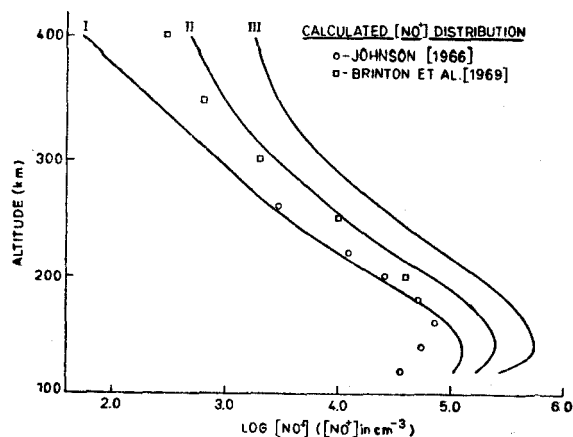


Fig. 10—Computed NO⁺ profiles for the three levels of solar activity and the observed data

the distribution is essentially photochemical. Computed profiles for the three levels of solar activity are shown in Fig. 9. The profile for low activity above 140 km is in good agreement with the results of Johnson¹⁵. In the altitude range 200-300 km the data of Brinton *et al.*⁹ are much higher compared to the calculated values for low activity.

4.5 NO⁺ Ions

This ion is produced in the F-region almost entirely by ion-neutral reactions. Important reactions for its production are 2, 5, 6, 9 and 14. The loss occurs entirely through dissociative recombination (reaction 18). For this ion also, the photochemical lifetime at 400 km is less than 1 min and hence the distribution is photochemical. Computed profiles and the data of Johnson¹⁵ and Brinton *et al.*⁹ are shown in Fig. 10. It will be seen that below 150 km the computed low activity profile deviates considerably from Johnson's data, and the data of Brinton *et al.*⁹ are in good agreement with the profile for medium activity.

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