

An Upper Atmospheric Model for Solar Minimum Conditions

V. P. BHATNAGAR AND A. P. MITRA

National Physical Laboratory, New Delhi, India

(Manuscript received 15 June 1965, in revised form 8 November 1965)

ABSTRACT

An atmospheric model for the height range 100–700 km, likely to hold for solar minimum conditions, has been developed. The flux density of solar radiation at 10.7 cm wavelength ($F_{10.7}$) is taken to be 70×10^{-22} w m^{-2} (cps)⁻¹. The model is based on extrapolation to 70 units, of density and density scale heights at different solar activity periods, in the height range of 250–700 km, deduced from drag observations of 46 satellites (King-Hele and Walker, 1961; Martin *et al.*, 1961; King-Hele and Rees, 1963; King-Hele and Quinn, 1965) during the period 1958 ($F_{10.7} \sim 230$ units) to early 1964 ($F_{10.7} \sim 80$ units), for diurnal minimum and maximum conditions. In the range of 100–250 km, density values obtained from various rocket flights to early 1964 ($F_{10.7} \sim 80$ units) have been used. The model gives the distribution of neutral particles, i.e., $n(\text{O}_2)$, $n(\text{N}_2)$, $n(\text{O})$, $n(\text{He})$, $n(\text{H})$; atmospheric scale height (H); mean molecular mass (\bar{m}); atmospheric temperature (T) and atmospheric pressure (p) with height up to 700 km. Diffusive equilibrium for N_2 , O_2 and O has been assumed to hold above 130 km, for He above 100 km and for H above 500 km. In the region of dissociation, observed values of $n(\text{O})/n(\text{O}_2)$ of Schaefer and Brown (1964) have been adopted. The results are discussed and compared with those given by other workers.

1. Introduction

Investigations through sounding rockets and satellites have established the fact that, in addition to a pronounced diurnal variation in upper atmospheric density, reaching a maximum about two hours after local noon (Jacchia, 1959; Wyatt, 1959; Priester and Martin, 1960) and a minimum between midnight (Jacchia, 1960; Jacchia and Slowey, 1962a) and dawn (Priester *et al.*, 1960a), large fluctuations also occur with solar activity. These variations with solar activity include erratic or 27 day variations with solar activity (Jacchia, 1959a), semi-annual and annual variations (Paetzold and Zschörner, 1960, 1961), and geomagnetic perturbations (Jacchia and Slowey, 1962, 1963, 1964), superimposed on the larger 11 year solar cycle variation in the upper atmosphere. Of these different types of variations, the largest are those due to variations in the solar cycle. It is thus obvious that no single atmospheric model can represent atmospheric parameters for all solar conditions.

Several models appropriate for different phases of solar activity are available in the literature. Models holding exclusively for high solar activity have been given by Mathur and Mitra (1960) for $F_{10.7} \sim 230$ units¹ and a height range of 130–1000 km, and by Paetzold and Zschörner (1961) for $F_{10.7} \sim 220$ units and Martin *et al.* (1961) for $F_{10.7} \sim 200$ units and height ranges of 150–1600 km and 130–1600 km, respectively. These models were based on the satellite drag data

available during the International Geophysical Year (IGY).

Atmospheric models appropriate for medium solar activity ($F_{10.7} \sim 175$ units) were prepared and published by COSPAR in 1961 and known as the COSPAR International Reference Atmosphere (CIRA, 1961). It was based on the best available density data to the beginning of 1961 and gave the atmospheric parameters up to an altitude of 800 km for diurnal minimum, average and maximum periods. Kallmann-Bijl and Sibley (1964) also gave an atmospheric model for $F_{10.7} \sim 150$ units based on the observed values of densities from satellites and rockets in the height range 100–500 km, for diurnal minimum and maximum conditions.

Apart from these, various atmospheric models, including a few likely to hold for solar minimum conditions, have been developed for a wide range of solar activities represented in terms of solar radio flux and exospheric temperature. These are as follows:

a) *Atmospheric models based on densities obtained from satellite drag observations.* From observations of satellite drag data available after the IGY and until 1962, Paetzold (1963) extended his previous atmospheric model for high solar activity (Paetzold and Zschörner, 1961) to other solar activities ($F_{10.7} = 120, 70$ units) over the height range 150–500 km for diurnal minimum and maximum conditions for November (annual maximum of his postulated plasma effect). Further, King-Hele *et al.* (1961, 1963, 1965) developed atmospheric models over the height range 200–700 km for different phases of solar activity ($F_{10.7} \sim 80$ –230 units) for diurnal minimum and maximum conditions, based on satellite

¹ The flux density of solar radiation at a wavelength of 10.7 cm. Units are in 10^{-22} w m^{-2} (cps)⁻¹.

drag observations during the period 1958 through early 1964. Satellite drag observations were also used to develop atmospheric models based on a direct proportionality between solar radio flux and density (Anderson, 1962) or on more complex empirical relationships (Marov, 1965).

b) Static atmospheric models based on heat conduction as the essential process. The first multi-temperature models, ranging from 773K to 2133K and above 120 km, were developed by Nicolet (1961a) on the basis of diffusive equilibrium. These various temperature profiles were derived from the model with highest exospheric temperatures by the conduction cooling of the atmosphere in the absence of external energy sources.

The boundary conditions were assumed to be invariant at 120 km. These models were further revised (Nicolet II, 1964) and are given in Jacchia's (1964) paper.

In order to achieve a better agreement with densities obtained from satellites, Jacchia (1964) further developed static atmospheric models for a wide range of exospheric temperatures from 650K to 2100K, starting from a fixed set of boundary conditions at 120 km. These models were based on empirical temperature profiles of exponential form derived from the synthesis of Nicolet, and Harris and Priester (1962) temperature profiles which were capable of reproducing densities determined from satellite drag observations.

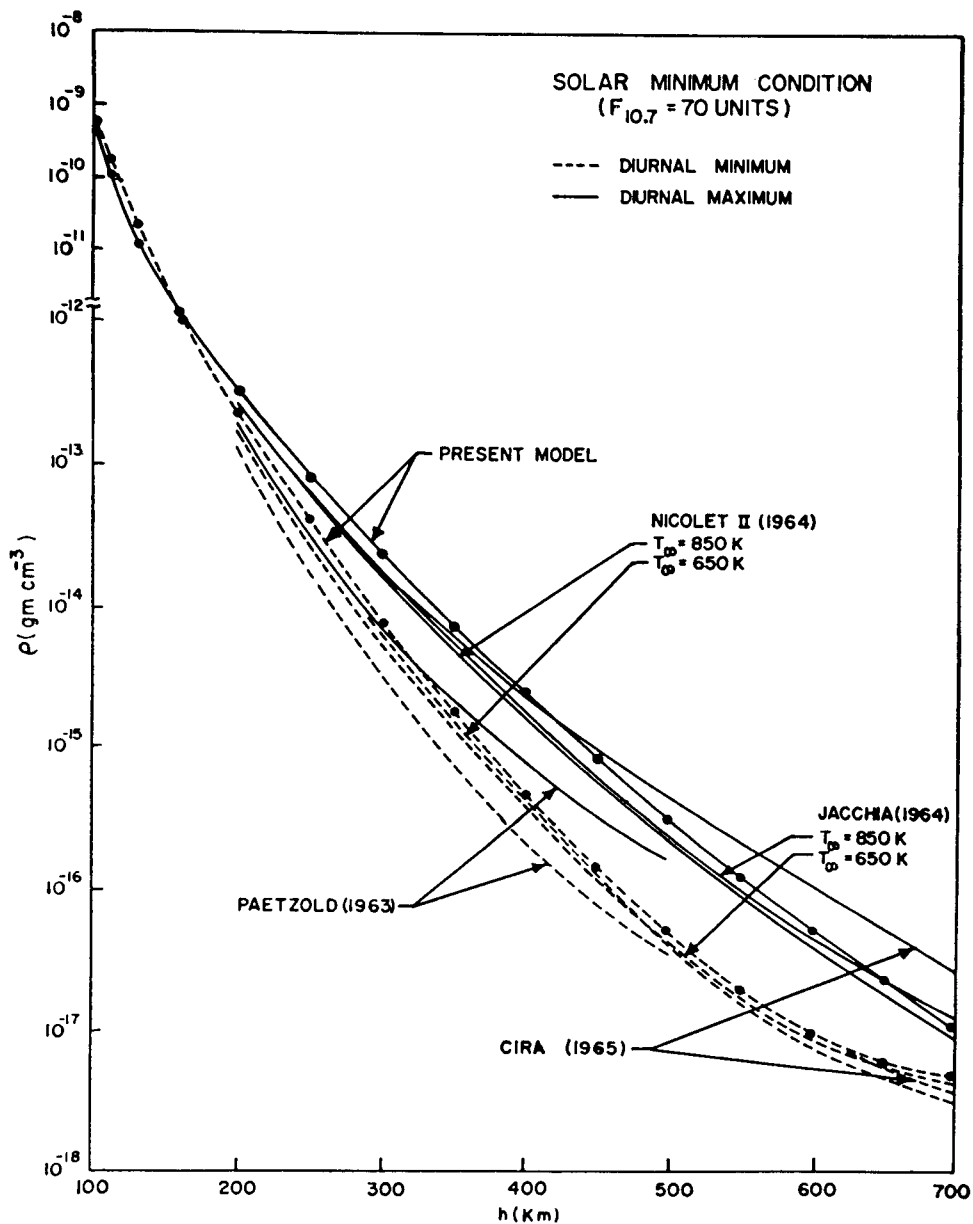


FIG. 1. Present density model and its comparison with other models for solar minimum conditions.

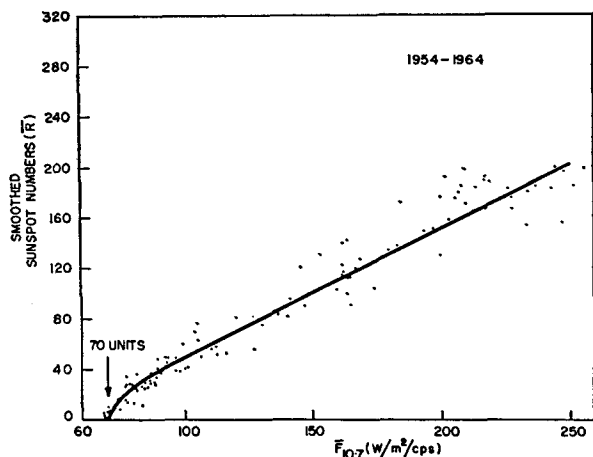


FIG. 2. Variation of smoothed sunspot numbers with monthly average of solar flux at 10.7 cm wavelength. Multiply abscissa by 10^{-22} to obtain units of $w m^{-2} (cps)^{-1}$.

c) *Time dependent atmospheric models based on heat conduction and hydrostatic equations.* Static atmospheric models are subject to a serious limitation due to the assumption of static equilibrium in an atmosphere with day to night temperature variations which have a period which is not likely to be larger than the heat conduction time from the lower thermosphere to the thermopause. This was clearly shown (Harris and Priester, 1962; CIRA, 1965) when Harris and Priester took account of the diurnal variation in the upper atmosphere. They performed a simultaneous integration of the heat conduction equation and the hydrostatic equation, taking into account the heat sources (solar x-ray and ultraviolet radiation and a hypothetical heat source) and sinks, the heat input being varied with a 24-hour cycle. They further assumed fixed boundary conditions at 120 km. However, the diffusion level for hydrogen was changed to 500 km in their later models (CIRA, 1965) from the value of 120 km used in their previous models (Harris and Priester, 1962).

It may be noted that although atmospheric models exist for various solar activities, individual particle concentrations have been derived in relatively few atmospheric models (Jacchia, 1964; CIRA, 1965) for solar minimum conditions. Further, the atmospheric models for declining phase of solar activity differ considerably at greater heights from each other and in the observed densities derived from satellite drag observations (Fig. 1).

It should further be noted that while diffusion starts around 120 km, it is not an isopycnic level as was assumed by Nicolet, Jacchia, and Harris and Priester, although there is evidence indicating a permanent isopycnic level near 90 km (Cole, 1961, 1965; Groves and McDermott, 1963). Rocket flights during the different solar activity periods also show that the atmospheric density and composition in the lower atmosphere are probably dependent on solar activity

and local time. Hence the boundary conditions adopted by Nicolet, Jacchia, and Harris and Priester may not be invariant with solar activity and local time.

As considerable new information has accumulated regarding the factors mentioned above in the past few years, an effort has been made in this paper to develop an atmospheric model for solar minimum conditions, for which a flux of $70 \times 10^{-22} w m^{-2} (cps)^{-1}$ has been used. This model is based on recent data of 1) the observed densities during the declining part of the solar cycle from rocket flights and satellites, 2) the dissociation of molecular oxygen close to minimum solar activity (Schaefer, 1963, 1964), and 3) the diffusion levels of the lighter constituents. The theoretical investigations on the distribution of lighter constituents by Nicolet (1961, 1962, 1963) and Kockarts and Nicolet (1962, 1963) show that the diffusion levels for helium and hydrogen start around 100 km and 500 km, respectively.

In this model, the particle densities of N_2 , O_2 , O, He and H together with scale height (H), mean molecular mass (\bar{m}), temperature (T) and pressure (p) are given over the heights 100–700 km from empirical mass density curves obtained for solar minimum conditions. The model thus developed is compared in Fig. 1 with those given by Nicolet II (see Jacchia, 1964), Paetzold (1963), and CIRA (1965). Discussions are given in Section 4.

2. Assumptions

The sunspot minimum atmospheric model, constructed and presented here, is based on the following assumptions:

- a) The 10.7-cm solar radio flux appropriate for solar minimum conditions is taken to be $70 \times 10^{-22} w m^{-2} (cps)^{-1}$ as shown in Fig. 2.
- b) An isopycnic level at 90 km has been assumed (Cole, 1961, 1965; Groves and McDermott, 1963).

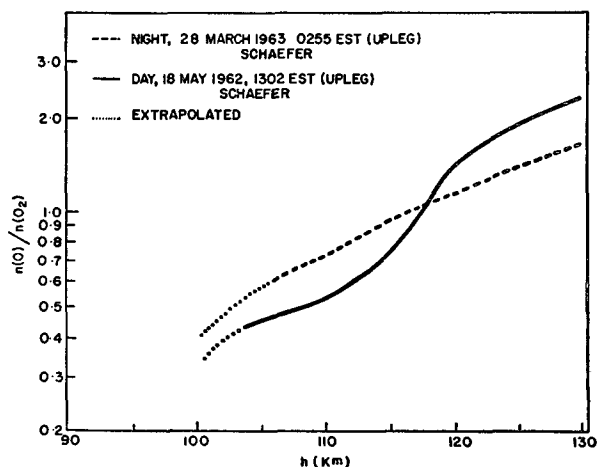


FIG. 3. Variation of $n(O)/n(O_2)$ with height.

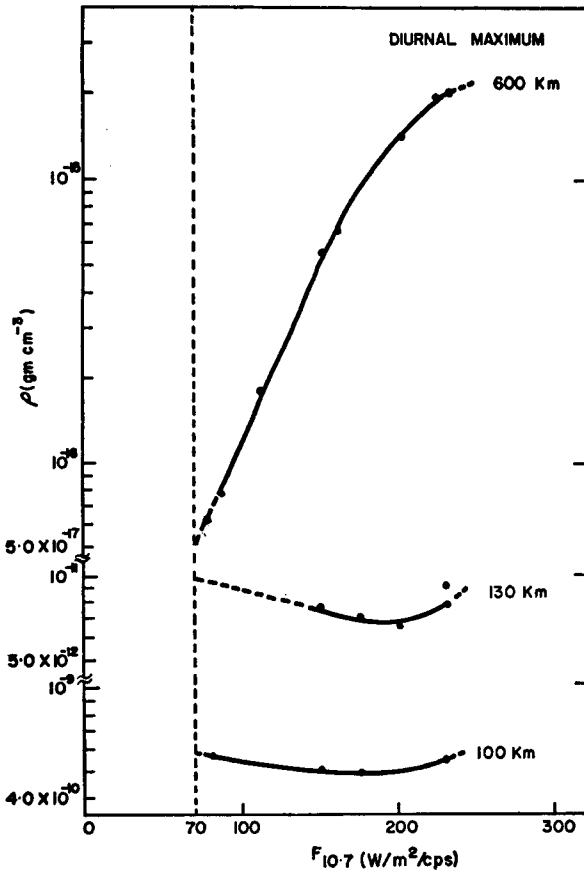


FIG. 4a. Extrapolation of densities at 600 km, 130 km and 100 km to 70 units for diurnal maximum conditions. Multiply abscissa by 10^{-22} to obtain units of w m^{-2} (cps) $^{-1}$.

It is further assumed that the density at this level is independent of solar activity.

c) The perfect gas law and the hydrostatic equation are assumed to be valid in the region investigated.

d) Dissociation of O_2 is taken to be virtually complete below 130 km and the observed values of Schaefer (1963, 1964) for nighttime and daytime conditions have been adopted (Fig. 3). However, it should be noted that the ratio of O/O_2 ion currents was assumed to be approximately the ratio of O/O_2 number densities.

e) Diffusion of N_2 , O_2 and O is taken to start from 130 km (Mathur and Mitra, 1960), diffusion of He from 100 km, (Nicolet, 1961a, 1962; Kallmann-Bijl and Sibley, 1964), and diffusion of H from 500 km (Kockarts and Nicolet, 1962, 1963; Nicolet, 1963).

3. Method

a) *Density curves for diurnal minimum and diurnal maximum conditions.* Empirical density curves for the diurnal minimum and maximum periods, in the height range from 250–700 km, have been obtained from the extrapolation to 70 units, of densities and density scale heights at various solar activities obtained from the drag data of a large number of satellites until early

1964 (Martin *et al.*, 1961; King-Hele and Walker, 1961; King-Hele and Rees, 1963; King-Hele and Quinn, 1965). However, at the lower heights, density values obtained from various rocket flights for different solar activity periods have been used (CIRA, 1961; Pokhunkov, 1963; Kallmann-Bijl and Sibley, 1964; Zimmerman, 1963; Groves, 1963; McDermott, 1963; Faire and Champion, 1965). Typical cases of extrapolation of density to 70 units of flux at 100 km, 130 km and 600 km for the diurnal maximum conditions are shown in Fig. 4a, while Fig. 4b gives the extrapolation of density at 300 km for both minimum and maximum conditions. The empirical density model thus obtained is shown in Fig. 1, where the dots represent the extrapolated values. King-Hele *et al.* (1963, 1965) give a probable limit of error for their density values of about 20 per cent. Since our extrapolation is based on these values, the error in the density values assumed for 70 units may also be expected to be of the same order. It should be noted that for the years 1962–1964, there are no daytime and nighttime density points above about 450 km and hence the extrapolated density curves given by King-Hele and Quinn (1965) may lack reliability. Similarly, the density curves given by King-Hele *et al.* (1963, 1965) for the nighttime of the years 1959, 1961 and the daytime of the year 1961, are all tentative above 600 km due to lack of density points and may therefore be in error. A density value of 3.12×10^{-9} gms cm^{-3} was adopted at 90 km from CIRA (1961).

b) *Determination of atmospheric scale height (H).* The vertical distribution of density as obtained from

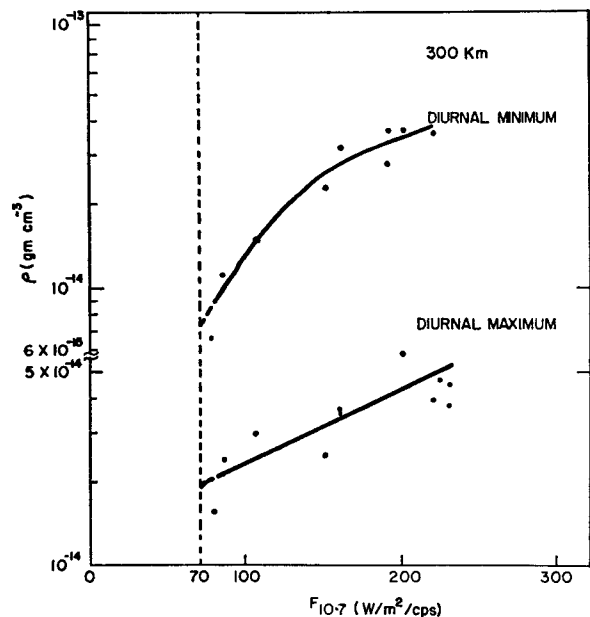


FIG. 4b. Extrapolation of densities at 300 km for diurnal minimum and maximum conditions. Multiply abscissa by 10^{-22} to obtain units of w m^{-2} (cps) $^{-1}$.

satellite drag data near its perigee can be given as

$$\rho = \rho_0 \exp\left(-\frac{h}{H_\rho}\right), \quad (1)$$

where $\rho = \rho_0$ at a reference height $h=0$, and H_ρ is the density scale height. It has been shown by Nicolet (1961a) that the atmospheric scale height H at a certain height can be related to H_ρ by

$$H = (1 + \beta)H_\rho, \quad (2)$$

where

$$\beta = dH/dh.$$

The two scale heights H and H_ρ are identical only when $\beta=0$. Further, if the gradient of β with height is neglected, then

$$\beta = \beta_\rho / (1 - \beta_\rho), \quad (3)$$

where $\beta_\rho = dH_\rho/dh$. It can be seen from Eqs. (2) and (3) that atmospheric scale height H and hence pressure p can be determined at any height 'h' from

$$p = H\rho g = (1 + \beta)H_\rho \cdot (\rho g), \quad (4)$$

where g is the acceleration of gravity. Eq. (4) was utilized to obtain the pressure at 700 km and, from the variation of density with height, the variation of pressure was determined down to 100 km from the hydrostatic equation. (Kallmann-Bijl, 1959; CIRA, 1961). The variation of atmospheric scale height H with height was then determined from

$$H = p/\rho g. \quad (5)$$

c) *Region of mixing.* From the density and the observed ratio of $n(O)/n(O_2)$, the concentrations of N_2 , O_2 , O and He were computed as follows:

In the region of dissociation of molecular oxygen, but below the diffusion level,

$$[n(O_2) + 0.5n(O)]/n(N_2) = 0.2683. \quad (6)$$

Hence

$$n(O_2) = 0.2683n(N_2)/(1 + 0.5x), \quad (7)$$

and

$$n(O) = xn(O_2). \quad (8)$$

Using Eqs. (6), (7) and (8) and neglecting He and H , as these are extremely small at these heights as compared to the major constituents N_2 , O_2 and O , one gets

$$n(N_2) = \rho / \left(28.02 + \frac{8.586}{1 + 0.5x} + \frac{4.293x}{1 + 0.5x} \right). \quad (9)$$

For helium, we take Nicolet's value (Nicolet, 1961, 1962),

$$n(He) = 6.7 \times 10^{-6} n(N_2). \quad (10)$$

Thus from a knowledge of the dissociation of molecular oxygen and the mass density, the concentration of N_2 , O_2 , O and He can be computed from Eqs. (7)–(10).

For atomic hydrogen, the diffusive equilibrium has been assumed to start from 500 km, where the following values were adopted from Kockarts and Nicolet (1963), for the exospheric temperature at 700K and 900K:

$$n(H)_{\min} \sim 3.5 \times 10^5 \text{ cm}^{-3}$$

$$n(H)_{\max} \sim 5.6 \times 10^4 \text{ cm}^{-3}.$$

However, for heights below 500 km, where the hydrogen distribution is strongly affected by the diffusive flow, its concentration has been adopted from Kockarts and Nicolet (1963) for the same exospheric temperature mentioned above. The mean molecular mass \bar{m} and temperature T were obtained from

$$\bar{m} = \rho/n = \sum_i n_i m_i / \sum_i n_i \quad (11)$$

and

$$T = H\bar{m}g/k, \quad (12)$$

where k is Boltzmann's constant (1.38×10^{-16} ergs $(^\circ\text{K})^{-1}$).

d) *Computation of n_i , H , T , and \bar{m} in the diffusive region.* The number density n_i for the i th constituent at the height h in the thermosphere was computed at height intervals of 10 km from the relation

$$n_i = n_{i0} \left(\frac{T}{T_0} \right)^{-\left(1 + \frac{m_i g}{k\alpha}\right)}, \quad (13)$$

where n_{i0} is the number density at the reference height h_0 , m_i is its mass, T is the atmospheric temperature at the height h , α is the temperature gradient dT/dh and g is the average acceleration due to gravity in the slab.

The temperature T in (13) was determined from (12) where H was taken from Eq. (5). The atmospheric mean molecular mass \bar{m} was determined, assuming \bar{m} to be constant for the slab, by first evaluating the total particle density n at the height h from

$$n = n_0 \left(\frac{H}{H_0} \right)^{-\left(\frac{1+\beta}{\beta}\right)}, \quad (14)$$

where $n_0 (= \sum_i n_{i0})$ at the height h_0 was taken from Eq. (13), as determined for the previous slab. Thus knowing n , \bar{m} at the height h was determined from

$$\bar{m} = \rho/n, \quad (15)$$

where ρ was taken from empirical mass density curves. The number densities n_i in the isothermal region, however, were computed from

$$n_i = n_{i0} \exp \left[-\frac{m_i g_0 (h - h_0) (R + h_0)}{kT(R + h)} \right], \quad (16)$$

where g_0 is the acceleration due to gravity at the height h_0 and R is the radius of the earth.

TABLE 1. Variation of atmospheric properties with altitude.

(a) Diurnal minimum

<i>h</i> km	ρ gms cm ⁻³	β dynes cm ⁻²	$n(N_2)$ cm ⁻³	$n(O_2)$ cm ⁻³	$n(O)$ cm ⁻³	$n(He)$ cm ⁻³	$n(H)$ cm ⁻³	n cm ⁻³	\bar{m}^{**}	<i>H</i> km	<i>T</i> °K
100	6.30-10*	4.19-1	1.04+13	2.32+12	9.30+11	6.94+7	1.00+7	1.36+13	27.9	6.9	219
110	1.40	1.11	2.30+12	4.58+11	3.21	4.79	3.00+6	3.08+12	27.3	8.4	262
120	4.00-11	3.85-2	6.58+11	1.14	1.25	3.43	1.40	8.97+11	26.9	10.2	312
130	1.30	1.53	2.14	3.19+10	5.10+10	2.51	9.70+5	2.97	26.4	12.5	374
140	5.11-12	7.53-3	8.20+10	1.09	2.71	1.85	7.70	1.20	25.6	15.7	453
150	2.35	4.18	3.66	4.44+9	1.59	1.43	6.90	5.69+10	25.0	19.0	535
170	7.42-13	1.71	1.06	1.11	7.16+9	9.98+6	6.10	1.89	23.7	24.8	659
200	2.19	5.59-4	2.65+9	2.22+8	3.16	8.18	5.50	6.04+9	21.8	27.7	670
250	3.61-14	1.06	2.69+8	1.62+7	8.55+8	5.90	5.10	1.15	19.0	32.3	670
300	7.67-15	2.50-5	2.83+7	1.23+6	2.36	4.28	4.75	2.70+8	17.1	36.4	670
350	1.94	6.80-6	3.09+6	9.76+4	6.65+7	3.12	4.40	7.32+7	15.9	39.8	670
400	5.39-16	2.04	3.46+5	8.05+3	1.91	2.28	4.10	2.21	14.7	43.6	670
450	1.62	7.11-7	4.02+4	6.84+2	5.57+6	1.68	3.75	7.67+6	12.7	51.3	670
500	5.31-17	3.02	4.82+3	6.02+1	1.66	1.24	3.50	3.25	9.8	67.4	670
600	9.16-18	1.06	7.59+1	5.26-1	1.55+5	6.84+5	3.02	1.14	4.8	141.8	670
700	3.40	6.11-8	1.34+0	5.21-3	1.55+4	3.84	2.61	6.61+5	3.1	225.8	670

(b) Diurnal maximum

100	5.70-10	3.47-1	9.38+12	2.20+12	6.17+11	6.29+7	1.00+7	1.22+13	28.1	6.4	206
110	9.29-11	7.81-2	1.53	3.23+11	1.74	3.82	2.60+6	2.03+12	27.6	8.9	280
120	2.50	2.81	4.11+11	6.49+10	9.09+10	2.59	7.50+5	5.67+11	26.5	11.9	358
130	9.49-12	1.34	1.56	2.01	4.36	1.87	3.80	2.20	26.0	15.0	443
140	4.00	7.55-3	6.40+10	7.56+9	2.34	1.31	2.30	9.50+10	25.4	20.1	578
150	2.12	4.84	3.29	3.63	1.49	1.03	1.80	5.14	24.8	24.4	682
170	8.29-13	2.31	1.20	1.18	7.83+9	7.80+6	1.20	2.10	23.8	30.0	799
200	2.90	9.30-4	3.68+9	3.08+8	3.85	6.17	9.70+4	7.84+9	22.3	34.8	860
250	6.80-14	2.43	6.17+8	3.97+7	1.39	4.78	8.40	2.05	20.0	39.4	860
300	1.87	7.37-5	1.06	5.30+6	5.06+8	3.71	7.60	6.21+8	18.1	44.1	860
350	5.92-15	2.49	1.87+7	7.28+5	1.88	2.90	7.10	2.10	17.0	47.7	860
400	2.05	9.03-6	3.37+6	1.03	7.07+7	2.27	6.50	7.65+7	16.2	50.8	860
450	7.55-16	3.48	6.24+5	1.50+4	2.69	1.78	6.00	2.94	15.5	53.9	860
500	2.91	1.42	1.19	2.25+3	1.04	1.41	5.60	1.20	14.6	58.1	860
600	4.95-17	3.05-7	4.60+3	5.50+1	1.63+6	8.84+5	4.98	2.57+6	11.6	75.3	860
700	1.10	1.05	1.95+2	1.50+0	2.69+5	5.63	4.45	8.77+5	7.5	119.8	860

* Denotes the power of 10.

** Average molecular weight.

4. Models for diurnal maximum and minimum conditions

The values of \bar{m} , H , T , the various n_i and the total particle density, n , obtained in this analysis are given in Table 1 and are plotted in Figs. 5 through 10. The mass density values given in the present model have been plotted in Fig. 1 together with Paetzold's (1963) and CIRA (1965) models for $F_{10.7}=70$ units, Nicolet's improved version (Nicolet II, 1964) of his previous models (Nicolet, 1961) given in Jacchia (1964), and Jacchia's (1964) models for exospheric temperatures (T_∞) of 650K and 850K. Nicolet and Jacchia's models for the above temperatures have been adopted, since these temperatures are close to the exospheric temperatures of the present model. It can be seen that during daytime the density values given by present model in the exosphere are lower than the CIRA (1965) model, but are higher than in other models. However, during nighttime the differences are smaller except for Paetzold's model which gives lower density values. A comparison of the different models at the representative heights of 200, 400 and 600 km is given in Table 2.

The density values can also be compared with some of the recent values obtained from the satellite Explorer 17. Thus a value of 1.66×10^{-14} gm cm⁻³ obtained on 24 June 1963 ($F_{10.7}=74$ units, $A_p^*=6$) at 4.4 hours local solar time at the 270 km perigee (Bryant, 1964) agrees well with 1.89×10^{-14} gm cm⁻³ at the diurnal minimum of the present model. In addition a value of 2.72×10^{-14} gm cm⁻³ was obtained on 21 May 1963, ($F_{10.7}=83$ units, $A_p^*=5$) at 13.3 hours local solar time at the same perigee altitude (Bryant,

TABLE 2. Mass densities according to various models.

	<i>h</i> (km)	Present model	Jacchia (1964)	Nicolet II (1964)	CIRA (1965)
Diurnal minimum	200	2.19-13	1.67-13	2.29-13	1.75-13
	400	5.39-16	3.62-16	3.89-16	4.93-16
	600	9.16-18	9.07-18	6.76-18	1.00-17
Diurnal maximum	200	2.90-13	2.55-13	3.31-13	2.25-13
	400	2.05-15	1.55-15	1.58-15	2.34-15
	600	4.95-17	4.16-17	3.63-17	1.01-16

* Daily planetary geomagnetic index.

1964), which is somewhat less than the value of 3.97×10^{-14} gm cm⁻³ at the diurnal maximum of the present model. It may be pointed out that the present empirical density curves refer to average diurnal minimum and maximum conditions, as they are based on the values given by the best fit curves of King-Hele *et al.* (1961, 1963, 1965) to the individual density values obtained for various phases of solar activity. It is thus possible that the present density values may differ at certain heights from individual density measurements obtained for this phase of solar activity. Further as pointed out earlier, the values of densities given here could possibly be in error by about 20 per cent, which is also the probable error in the individual density values determined from satellite drag measurements.

Density data were also recently obtained during April to July, 1963 from Explorer 17 in the altitude range of 255 to 300 km for local times between 0700 and 2100 hours (Newton *et al.*, 1964). At the times of measurement, the daily planetary geomagnetic index was between 0 and 50, and the 10.7 cm solar flux was between 70 and 100×10^{-22} w m⁻² (cps)⁻¹. It was found that a considerable variation in density occurred at a given altitude, due in part to local time, geomagnetic activity, and solar activity effects. The absolute accuracy of the data was believed to be ± 35 per cent.

At 300 km, the density varied by about a factor of about 6 from approximately 3.5×10^{-15} to 2.0×10^{-14} gm cm⁻³. Assuming that the densities determined by satellite drag techniques appear to be systematically higher (Newton *et al.*, 1964) by at least a factor of 2 than the gage densities, it can be seen that the density values from the present model, i.e., 7.7×10^{-15} gm cm⁻³ and 1.9×10^{-14} gm cm⁻³ for diurnal minimum and maximum conditions (Fig. 4b) respectively, lie in the above range.

It has been found previously (King-Hele and Walker, 1961; Priester *et al.*, 1960a and Jacchia, 1961) that the mass densities above about 200 km during daytime are higher than nighttime densities. In Fig. 1 it can be seen that daytime densities above about 200 km are higher than nighttime densities.

However, below about 200 km, the daytime densities are lower than the nighttime densities. This was predicted earlier on theoretical grounds (Martin *et al.*, 1961) based on the law of conservation of mass which requires that the increase in densities at greater heights be compensated by a decrease in densities at lower heights and vice versa. This was also experimentally confirmed by the observations of Horowitz and Lagow (1957, 1958), Horowitz *et al.*, (1959), Meadows and Townsend (1960), McDermott and Groves (1962), Pokhunkov (1963), and Faire and Champion (1965).

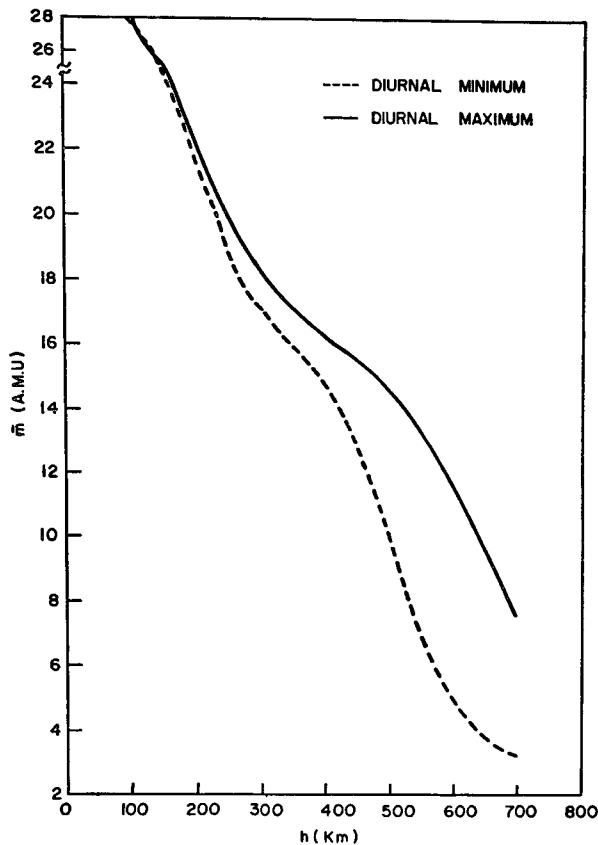


FIG. 5. Variation of mean molecular mass with height.

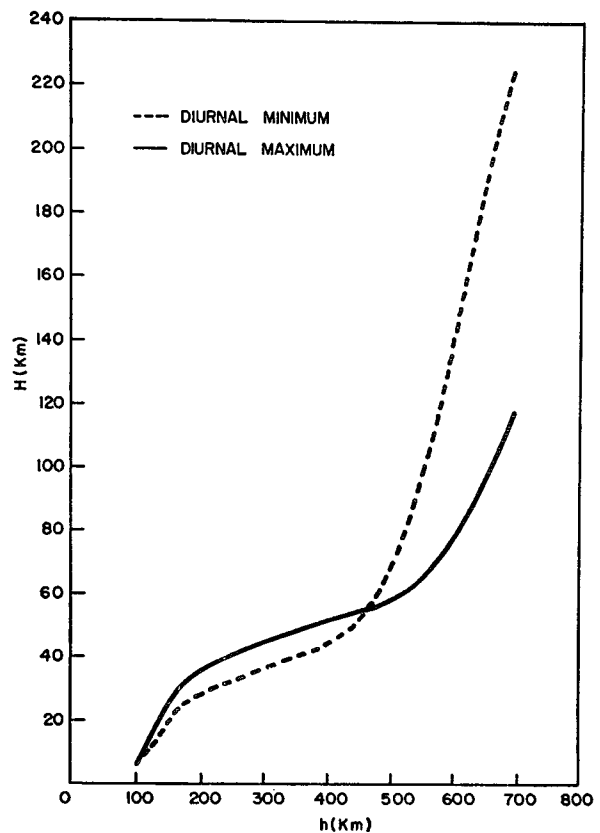


FIG. 6. Variation of atmospheric scale height with height.

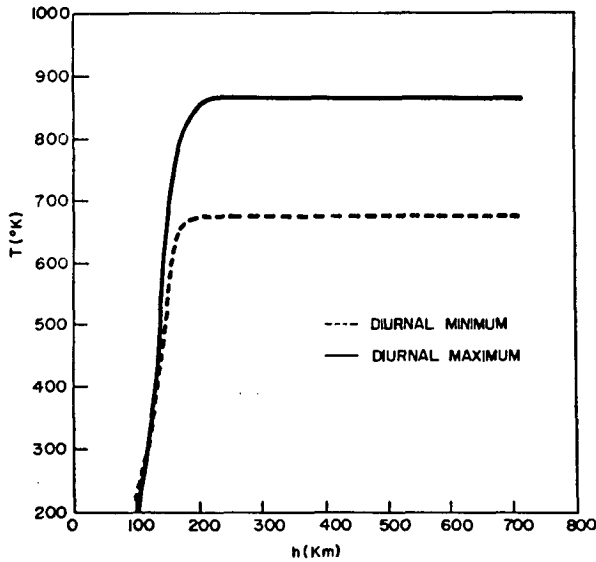


FIG. 7. Variation of temperature with height.

The higher nighttime densities below about 200 km can also be noted in the Kallmann-Bijl (1964) curves for mass densities for late 1960 and in the Harris and Priester (1962) and CIRA (1965) models.

The variation of mean molecular mass (\bar{m}) with altitude is shown in Fig. 5. It can be seen that \bar{m} continues

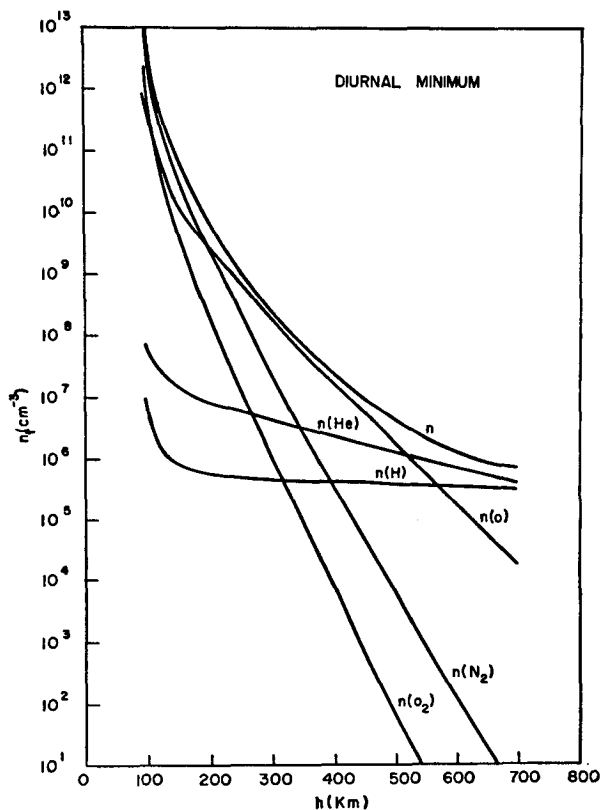


FIG. 8. Distribution of $n(O_2)$, $n(N_2)$, $n(O)$, $n(He)$, $n(H)$ and total particle density n with height for diurnal minimum conditions.

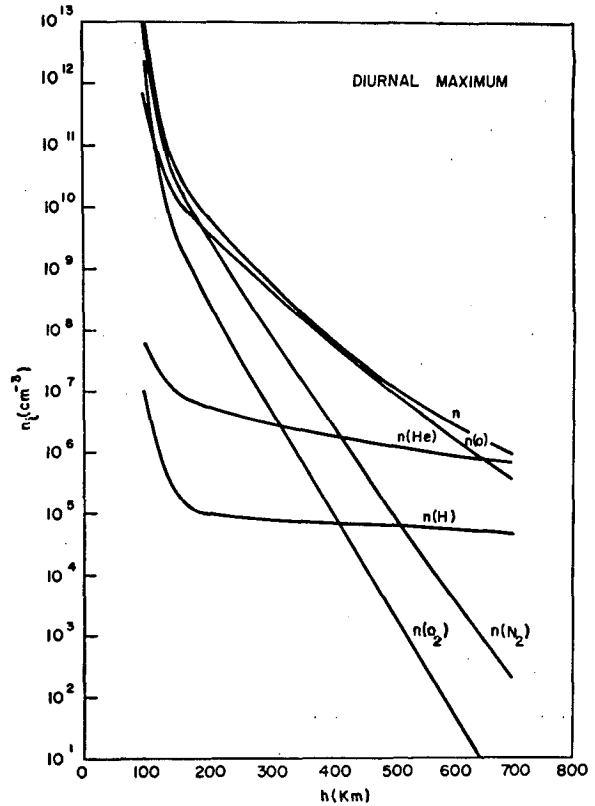


FIG. 9. Distribution of $n(O_2)$, $n(N_2)$, $n(O)$, $n(He)$, $n(H)$ and total particle density n with height for diurnal maximum conditions.

to decrease from 27.9 at 100 km to 3.1 at 700 km for the diurnal minimum conditions, and from 28.1 to 7.5 for diurnal maximum conditions.

Fig. 6 shows the variation of smoothed scale height (H) values for the usual two conditions. During nighttime, H continues to increase from about 7 km at 100 km to about 226 km at 700 km, while during daytime it increases from about 6.4 km to about 120 km in the same height range.

Fig. 7 shows the variation of temperature for nighttime and daytime conditions. It can be seen that most of the temperature rise occurs below about 200 km. The temperature increases from about 219K at 100 km to 670K around 180 km during nighttime and probably remains constant above this height. For daytime, the temperature increases from about 206K at 100 km to 860K at about 200 km, above which it probably remains constant. It may be noted, however, that while computing temperature from Eq. (14) a scatter of about 2 per cent was found around the temperature profile shown in Fig. 7. The daytime maximum temperature

TABLE 3. Geometric height of transition for various ions.

	$O^+ - He^+$	$He^+ - H^+$	$O^+ - H^+$
Diurnal minimum	520 km	780 km	570 km
Diurnal maximum	640 km	1525 km	800 km

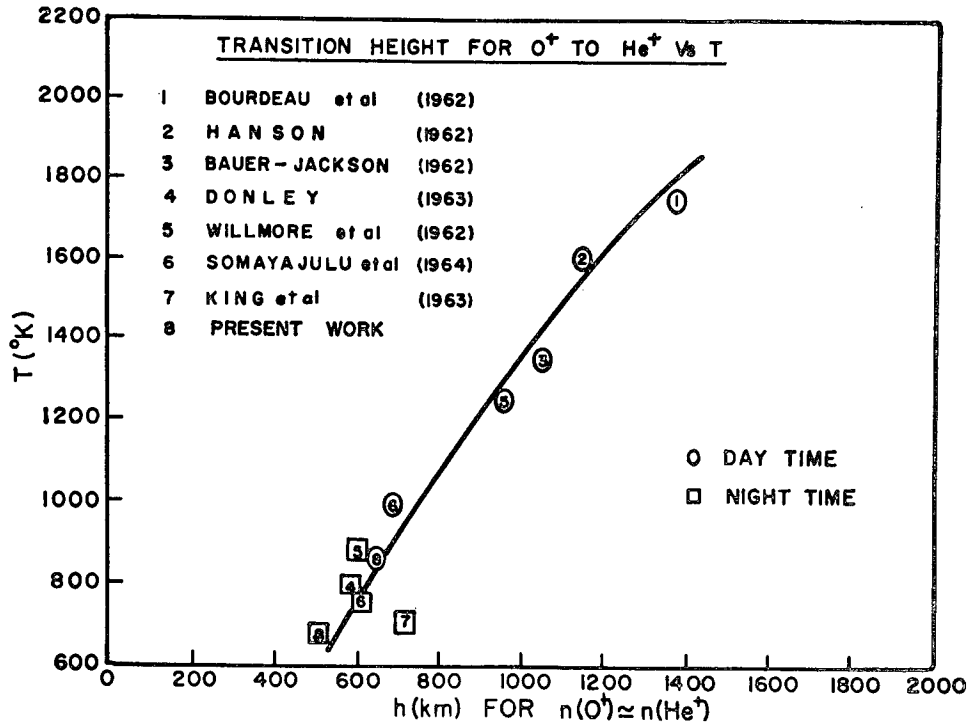


Fig. 10a. Transition altitude for O⁺ to He⁺ as a function of temperature.

is higher than the nighttime minimum by a factor of 1.28. This factor is quite close to the earlier values of 1.35 and 1.33 given by Jacchia (1961), and Jacchia and Slowey (1962a), suggesting that this factor seems to

remain unchanged in the course of the 11-year solar cycle.

The variation of n_i 's with height is shown in Figs. 8 and 9 for diurnal minimum and maximum conditions.

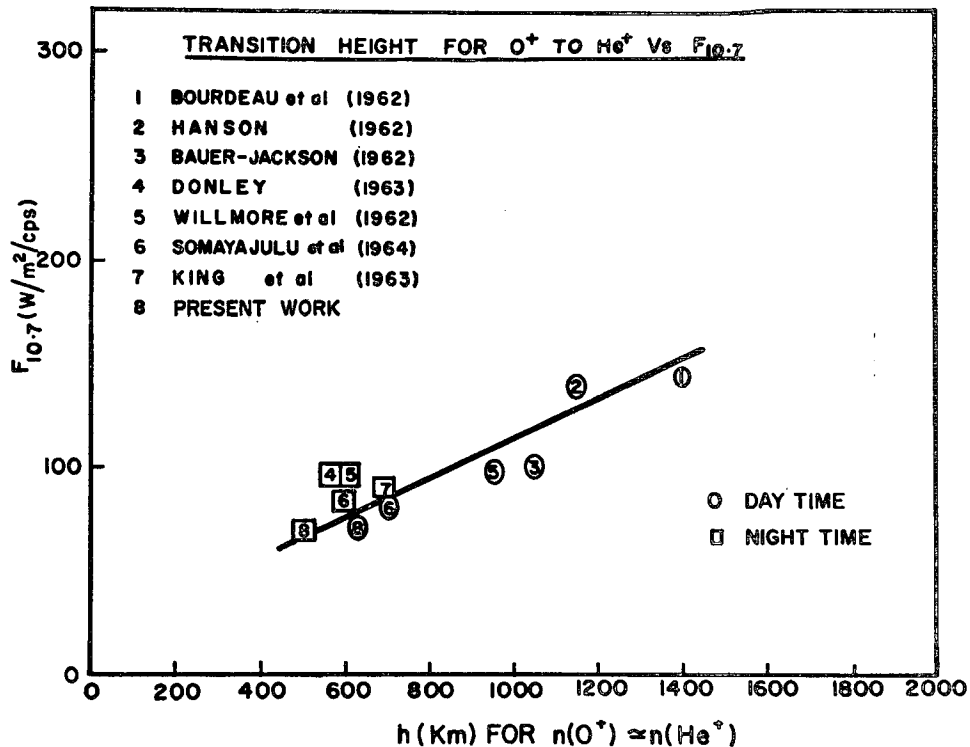


Fig. 10b. Transition altitude for O⁺ to He⁺ as a function of solar flux at 10.7 cm.

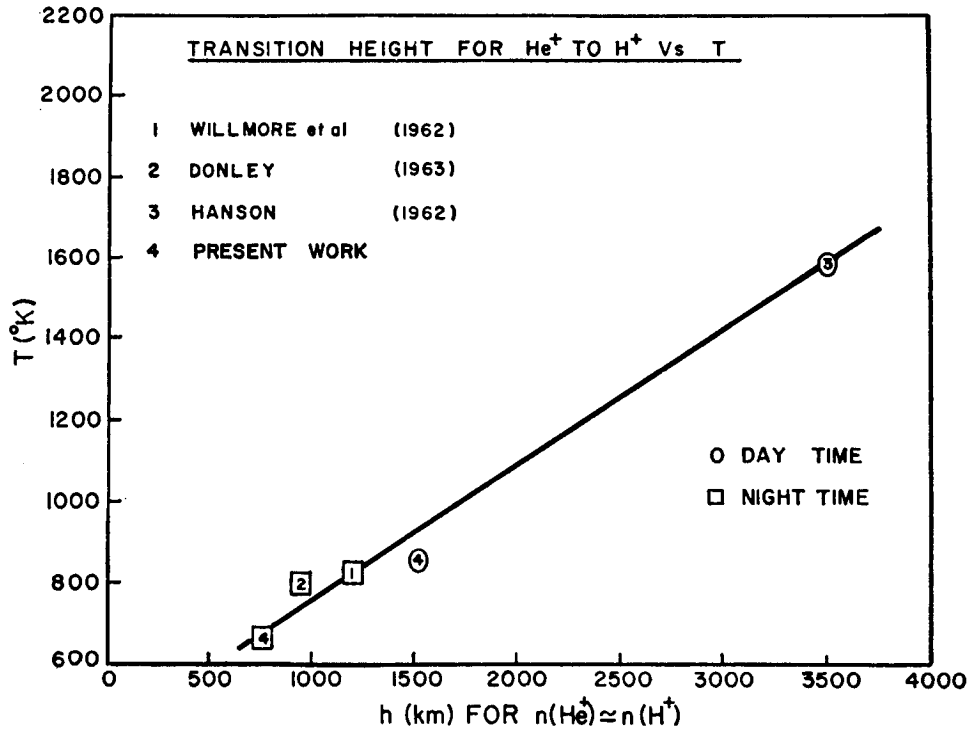


FIG. 11a. Transition altitude for He⁺ to H⁺ as a function of temperature.

In these figures one can see the changing roles of the constituents with altitude. During diurnal minimum, $n(O)$, which is predominant above about 200 km, becomes equal to $n(He)$ at about 510 km, having a concentration of about $1.1 \times 10^6 \text{ cm}^{-3}$ and is equal to

$n(H)$ at about 570 km having a concentration of about $3.1 \times 10^5 \text{ cm}^{-3}$. During diurnal maximum conditions, it can be seen that $n(O)$ which is again predominant above about 200 km, becomes equal to $n(He)$ at about 640 km, having a value of about $7.2 \times 10^5 \text{ cm}^{-3}$, and

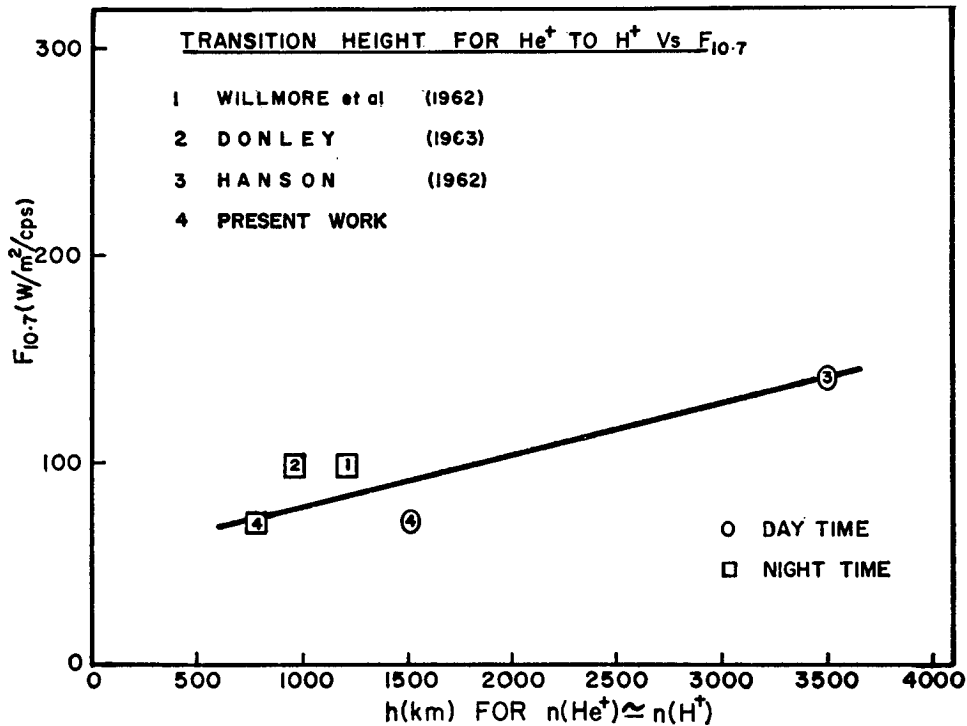


FIG. 11b. Transition altitude for He⁺ to H⁺ as a function of solar flux at 10.7 cm.

appears to become equal to $n(\text{H})$ when extrapolated to a value of $4.0 \times 10^4 \text{ cm}^{-3}$ at about 800 km. It can also be seen that helium predominates over hydrogen in the whole region of investigation in both cases, the latter being a minor constituent below about 300 km for nighttime minimum and below about 400 km for daytime maximum. Also the concentration of helium above 100 km does not amount to more than $6 \times 10^7 \text{ cm}^{-3}$, in accordance with the observational data (Pokhunkov, 1963).

However, it must be pointed out that at lower heights the particle concentrations may be slightly in error due to the neglect of argon, which is an important constituent at these heights. Atomic nitrogen and nitric oxide have also been neglected since they are likely to be minor constituents in the thermosphere (Barth, 1961; Nicolet, 1962, 1963) and more quantitative data are needed to estimate their variation. Further observational data on the concentration of atomic nitrogen by Schaefer and Nichols (1964a) shows that its concentration below 190 km does not exceed 5 per cent of N_2 . However, according to Pokhunkov (1963), the atomic nitrogen concentration in the nighttime atmosphere in the range of 100–210 km does not exceed 1–2 per cent of N_2 concentration. As regards NO, its concentration at altitudes of 130–180 km during nighttime, does not exceed 0.1 per cent of N_2 concentration (Pokhunkov, 1963).

5. Ionic transition heights

On the basis of the vertical distribution of neutral constituents, the corresponding transition heights for the ions have been determined. Assuming that the ionic species in the upper ionosphere are in diffusive equilibrium (Dungey, 1955; Mange, 1960), the geopotential altitude (h'_{ij}) at which two ionic species have equal concentrations, and hence the transition height, has been given by Bauer (1962) as

$$h'_{ij} - h'_0 = H_{ij} \ln(\eta_{ij}),$$

where h'_0 is the geopotential altitude at which the concentrations of these ions are in the ratio η_{ij} , and

$$H_{ij} = kT(m_i - m_j)g'_0$$

T = atmospheric temperature

g'_0 = acceleration due to gravity at the Earth's surface

m_i = mass of the heavier ion

m_j = mass of the lighter ion, and

$$\eta_{ij} = n_i(h'_0)/n_j(h'_0).$$

Bauer (1963) has further shown that the relative concentration of the ionic species at a given height, say h'_0 , should vary with temperature in the same proportion as the corresponding neutral constituents. A reference height h_0 of 400 km (geometric) was chosen here, at which the ratios of the ionic species were assumed to be equal to the corresponding neutral ones from the present model. The resulting values for the

transition heights of various ionic species are given in Table 3.

These various transition levels are plotted against temperature and solar flux at 10.7 cm and compared with observed values in Figs. 10a, 10b, 11a and 11b.

It can be seen that the agreement is quite satisfactory. However, for the transition height of O^+ to H^+ , only a few values ranging from 550 km to 800 km for low solar activity (King *et al.*, 1963; Sagalyn and Smiddy, 1964; Somayajulu *et al.*, 1965) are available and hence efforts have not been made to plot them against temperature and solar flux.

Acknowledgments. We gratefully acknowledge the valuable discussions with Dr. A. K. Saha of the Radio Propagation Unit.

REFERENCES

- Anderson, A. D., 1962: A simple model for atmospheric density variations from 200 to 800 km. *J. Atmos. Sci.*, **19**, 207–217.
- Barth, C. A., 1961: Nitrogen and oxygen atomic reactions in the Chemosphere, *Chemical Reactions in the Lower and Upper Atmosphere*, New York, Interscience Publishers, 303–326.
- Bauer, S. J., 1962: On the structure of the topside ionosphere. *J. Atmos. Sci.*, **19**, 276–278.
- , 1963: Helium ion belt in the upper atmosphere. *Nature*, **197**, 36–37.
- , and J. E. Jackson, 1962: Rocket measurement of the electron density distribution in the topside ionosphere. *J. Geophys. Res.*, **67**, 1675–1677.
- Bourdeau, R. E., E. C. Whipple, J. L. Donley and S. J. Bauer, 1962: Experimental evidence for the presence of helium ions based on Explorer VIII satellite data. *J. Geophys. Res.*, **67**, 467–475.
- Bryant, R., 1964: Densities obtained from drag on Explorer 17 satellite. *J. Geophys. Res.*, **69**, 1423–1425.
- Cole, A. E., 1961: Suggestion of a second isopycnic level at 80 to 90 km over Churchill, Canada. *J. Geophys. Res.*, **66**, 2773–2778.
- , 1965: Atmospheric structure up to 90 km. *Space Research*, Amsterdam, North-Holland Publishing Co., **5**, 1242–1423.
- CIRA, 1961: *COSPAR International Reference Atmosphere*. Amsterdam, North-Holland Publishing Co., 177 pp.
- , 1965: *COSPAR International Reference Atmosphere*. Amsterdam, North-Holland Publishing Co., 313 pp.
- Donley, J. L., 1963: Experimental evidence for a low ion-transition altitude in the upper nighttime ionosphere. *J. Geophys. Res.*, **68**, 2058–2060.
- Dungey, J. W., 1955: Electrodynamics of the outer atmosphere. *The Physics of the Ionosphere*, London, Physical Society, 229 pp.
- Faire, A. C., and K. S. W. Champion, 1965: Falling sphere measurements of atmospheric density, temperature and pressure up to 115 km. *Space Research*, **5**, Amsterdam, North-Holland Publishing Co., 1039–1057.
- Groves, G. V., 1963: Reported in 'Atmospheric Structure and its variations in the lower thermosphere.' *COSPAR Symposium*, Warsaw.
- , and D. P. McDermott, 1963: Reported in 'Atmospheric structure and its variations in the lower thermosphere.' *COSPAR Symposium*, Warsaw.
- Hanson, W. B., 1962: Upper atmosphere helium ions. *J. Geophys. Res.*, **67**, 183–188.
- Harris, I., and W. Priester, 1962: Time dependent structure of the upper atmosphere. Goddard Space Flight Center, NASA, Rep. X-640-62-69; Theoretical models for the solar-cycle variation of the upper atmosphere. Goddard Space Flight Center, NASA, Rep. X-640-62-70.

- Horowitz, R., and H. E. Lagow, 1957: Upper air pressure and density measurements from 90 to 220 kms with the Viking 7 rocket. *J. Geophys. Res.*, **62**, 57-77.
- , and —, 1958: Summer day auroral-zone atmospheric structure measurements from 100 to 210 kms. *J. Geophys. Res.*, **63**, 757-772.
- , —, and J. F. Guiliani, 1959: Fall-day auroral zone atmospheric structure measurement from 100 to 188 km. *J. Geophys. Res.*, **64**, 2287-2294.
- Jacchia, L. G., 1959: Solar effects on the acceleration of artificial satellites. *Smithsonian Astrophys. Obs. Rep.* No. 29.
- , 1959a: Two atmospheric effects of the orbital acceleration of artificial satellites. *Nature*, **183**, 526-529.
- , 1960: A variable atmospheric density model from satellite accelerations. *J. Geophys. Res.*, **65**, 2775-2781.
- , 1961: A working model for the upper atmosphere. *Nature*, **192**, 1147-1148.
- , 1964: Static diffusion models of the upper atmosphere with empirical temperature profiles. *Smithsonian Astrophys. Obs. Rep.* No. 170.
- Jacchia, L. G., and J. Slowey, 1962: Preliminary analysis of the atmospheric drag of the 12 foot balloon satellite (1961 delta 1). *Smithsonian Astrophys. Obs. Rep.* No. 84.
- , and —, 1962a: Accurate drag determinations for eight artificial satellites, atmospheric densities and temperatures. *Smithsonian Astrophys. Obs. Rep.* No. 100.
- , and —, 1963: An analysis of the atmospheric drag of the Explorer IX satellite from precisely reduced photographic observations. *Smithsonian Astrophys. Obs. Rep.* No. 125.
- , and —, 1964: Temperature variations in the upper atmosphere during geomagnetic quiet intervals. *Smithsonian Astrophys. Obs. Rep.* No. 152.
- Kallmann-Bijl, H. K., 1959: A preliminary model atmosphere based on rocket and satellite data. *J. Geophys. Res.*, **64**, 615-623.
- , and W. Sibley, 1964: Diurnal variation of temperature and particle density between 100 km and 500 km. *Space Research*, **4**, Amsterdam North-Holland Publishing Co., 279-301.
- King, J. W., P. A. Smith, D. Eccles and H. Helm, 1963: The structure of the upper ionosphere as observed by the topside sounder satellite Alouette. DSIR Radio Res. Sta. (Slough) Doc. RBS/1. M. 94.
- King-Hele, D. G., and E. Quinn, 1965: The variation of upper atmosphere density between sunspot maximum (1957-58) and minimum (1964). *J. Atmos. Terr. Phys.*, **27**, 197-209.
- , and J. M. Rees, 1963: The decrease in upper atmosphere density between 1957 and 1963, as revealed by satellite orbits. *J. Atmos. Terr. Phys.*, **25**, 495-506.
- , and D. M. C. Walker, 1961: Upper atmosphere density during the years 1957 to 1961, determined from satellite orbits. *Space Research*, **2**, Amsterdam, North-Holland Publishing Co., 918-957.
- Kockarts, G., and M. Nicolet, 1962: Le problème aéronomique de l'hélium et de l'hydrogène neutres. *Annales Géophys.*, **18**, 269-290.
- , and —, 1963: L'hélium et l'hydrogène atomique au cours d'un minimum d'activité solaire. *Annales Géophys.*, **19**, 370-385.
- Mange, P., 1960: The distribution of minor ions in electrostatic equilibrium in the high atmosphere. *J. Geophys. Res.*, **65**, 3833-3834.
- Marov, M. Y., 1965: Some additional data on atmospheric density at altitudes of 200-300 km. *COSPAR Symposium*, Buenos Aires, Argentina.
- Martin, H. A., W. Neveling, W. Priester and M. R. Roemer, 1961: Model of the upper atmosphere from 130 through 1600 km, derived from satellite orbits. *Space Research*, **2**, Amsterdam, North-Holland Publishing Co., 902-917.
- Mathur, S. B., and A. P. Mitra, 1960: Densities, temperatures and concentrations of atmospheric constituents from 130 to 1000 km. *J. Sci. Industr. Res. (India)*, **19A**, 311-317.
- McDermott, D. P., 1963: Reported in 'Atmospheric Structure and its variations in the lower thermosphere.' *COSPAR Symposium*, Warsaw.
- , and G. V. Groves, 1962: Solar effects on air density at 200 and 230 km. *Space Research*, **3**, Amsterdam, North-Holland Publishing Co., 19-26.
- Meadows E. B., and J. W. Townsend, 1960: IGY rocket measurements of arctic atmospheric composition above 100 km. Amsterdam, North-Holland Publishing Co., **1**, *Space Research*, 175-198.
- Newton, G., R. Horowitz and W. Priester, 1964: Atmospheric densities from explorer 17 density gages and a comparison with satellite drag data. *J. Geophys. Res.*, **69**, 4690-4692.
- Nicolet, M., 1961: Helium, an important constituent in the lower exosphere. *J. Geophys. Res.*, **66**, 2263-2264.
- , 1961a: Density of the heterosphere related to temperature. *Smithsonian Astrophys. Obs. Rep.* No. 75.
- , 1962: A representation of terrestrial atmosphere from 100 to 3000 km. Penn. State Univ. Sci. Rep. No. 155.
- , 1963: The composition and structure of terrestrial atmosphere. Penn. State Univ. Sci. Rep. No. 185.
- Nicolet, M-II, 1964: Given in, Static diffusion models of the upper atmosphere with empirical temperature profiles, *Smithsonian Astrophys. Obs. Rep.* No. 170.
- Paetzold, H. K., 1963: Solar activity effects in the upper atmosphere deduced from satellite observations. *Space Research*, **3**, Amsterdam, North-Holland Publishing Co., 28-52.
- , and H. Zschörner, 1960: Bearings of Sputnik III and the variable acceleration of satellites. *Space Research*, **1**, Amsterdam, North-Holland Publishing Co., 24-36.
- , and —, 1961: The structure of the upper atmosphere and its variations after satellite observations. *Space Research*, **2**, Amsterdam, North-Holland Publishing Co., 958-973.
- Pokhunkov, A. A., 1963: Gravitational separation, composition and the structural parameters of the atmosphere at altitudes above 100 km. *Space Research*, **3**, Amsterdam, North-Holland Publishing Co., 132-142.
- Priester, W., and H. A. Martin, 1960: Solare und tageszeitliche effekte in der Hochatmosphäre aus Beobachtungen künstlicher Erdsatelliten. *Mitt. Univ. Sternw., Bonn*, No. 29.
- , —, and K. Kramp, 1960a: Diurnal and seasonal density variation in the upper atmosphere. *Nature*, **188**, 202-204.
- Sagalyn, R. C., and M. Smiddy, 1964: Electrical processes in the nighttime exosphere. *J. Geophys. Res.*, **69**, 1809-1823.
- Schaefer, E. J., 1963: The dissociation of oxygen measured by a rocket-borne mass spectrometer. *J. Geophys. Res.*, **68**, 1175-1176.
- , and J. Brown, 1964: Additional rocket-borne mass spectrometer measurements of the dissociation of oxygen. *J. Geophys. Res.*, **69**, 1455-1456.
- , and M. H. Nichols, 1964a: Neutral composition obtained from a rocket-borne mass spectrometer. *Space Research*, **4**, Amsterdam, North-Holland Publishing Co., 205-234.
- Somayajulu, Y. V., T. R. Tyagi and V. P. Bhatnagar, 1965: Upper F-region profiles during low solar activity derived from observations on Faraday fading of satellite transmissions. *Space Research*, **5**, Amsterdam, North-Holland Publishing Co., 641-651.
- Willmore, A. P., R. L. F. Boyd and P. J. Bowen, 1962: Some preliminary results of the plasma probe experiments on Aerial satellite. *Proc. of the Intern. Conf. on the Ionosphere*, The Institute of Physics and Physical Society, London, 517-522.
- Wyatt, S. P., 1959: Solar effects in the motion of Vanguard. *Nature*, **184**, 351-352.
- Zimmermann, S. P., 1963: Reported in 'Atmospheric Structure and its variations in the lower thermosphere.' *COSPAR Symposium*, Warsaw.