REPRINTED FROM: CASE FILE COPY

SPACE RESEARCH III

PROCEEDINGS

OF THE THIRD INTERNATIONAL SPACE SCIENCE SYMPOSIUM

WASHINGTON, APRIL 30-MAY 9, 1962

EDITED BY

W. PRIESTER

1963

NORTH-HOLLAND PUBLISHING COMPANY—AMSTERDAM

STRUCTURE OF THE UPPER ATMOSPHERE DEDUCED FROM CHARGED PARTICLE MEASUREMENTS ON ROCKETS AND THE EXPLORER VIII SATELLITE

R. E. BOURDEAU and S. J. BAUER

National Aeronautics and Space Administration,
Goddard Space Flight Center, Greenbelt, Md., USA

Abstract: Ion composition measured directly at altitudes above the F2 peak on the Explorer VIII Satellite is compared with that obtained indirectly from recent rocket measurements of charged particle densities. These data show that there are two transition regions (from oxygen to helium ions and from helium to hydrogen ions) in the upper ionosphere rather than a single transition from oxygen to hydrogen ions as previously believed. The results place the altitude at which the ratio O^+/He^+ has a value of unity between 800 and 1400 km depending on the atmospheric temperature. The atmospheric temperature was measured simultaneously and in the upper ionosphere was found to be constant with altitude within a few percent. The experimental data are consistent with a previously-developed empirical relationship which predicts the altitude of the two transition levels as a function of diurnal time and of solar cycle.

Langmuir probe measurements of electron temperature made on the Explorer VIII Satellite together with those obtained on recent rocket flights are compared with reference atmospheres. This comparison favors the concept of temperature equilibrium in all but the lower F region of the quiet daytime ionosphere. A revision of theoretical considerations based on present knowledge of ionizing radiation and energy transfer mechanisms is offered as an explanation for the observed detailed altitude dependence of the difference between electron and neutral gas temperatures. A diurnal temperature variation of about eighty percent is indicated in the isothermal altitude region of the upper atmosphere from a comparison of Explorer VIII data and several rocket measurements of charged particle densities.

Резюме: Ионный состав, измеренный непосредственно выше максимума слоя F_2 при помощи спутника Эксплорер VIII сравнивается с данными, полученными косвенным образом из последних ракетных измерений, плотностей заряженных частиц. Эти данные показали, что в верхних слоях ионосферы существует скорее две переходные области (от ионов кислорода к ионам гелия и от ионов гелия к ионам водорода), чем одна – от ионов кислорода к ионам водорода, как полагали ранее. Результаты сравнений показали, что высота, на которой отношение O^+/He^+ имеет значение единицы, находится между 800 и 1400 км и зависит от температуры атмосферы. Одновременно измерялась температура атмосферы и было обнаружено, что в верхних слоях ионосферы при изменении высоты температура постоянна в пределах нескольких процентов. Экспериментальные данные согласуются с ранее выведенными отношениями, которые определяют высоту двух переходных уровней как функцию суточного времени и цикла солнечной активности. Измерения температуры при помоши зонда Лангмюра, проведенные на спутнике Эксплорер VIII вместе с измерениями, полученными на ракетах сравниваются со стандартными атмосферами. Результат сравнения согласуется с общим представлением о температурном равновесии во всех областях ниже области F в спокойной дневной ионосфере. Для объяснения различия наблюдаемого высотного хода электронной температуры и температуры нейтрального газа предлагается пересмотреть теоретические соображения, основываясь на современном уровне знания, касающегося излучения и механизмов переноса энергии. Показано, что различие суточной температуры в изотермической области верхней атмосферы, полученная при сравнении данных спутника Эксплорер VIII с данными нескольких ракетных измерений плотностей заряженных частиц, составляет 80%.

1. Introduction

The structure of the upper atmosphere is defined in terms of its density, temperature and chemical composition. This report presents results on the structure of the *ionized* atmosphere. The value of the charged particle data is enhanced when, as is done here, they are compared with recent reference atmospheres and solar radiation observations.

2. Ionic composition

To establish a basis for discussion of the most recent ion composition results, it is desirable to summarize our knowledge of upper atmosphere ionic composition as it existed a year ago. The ions formed in the greatest numbers in the lower ionosphere are N_2^+, O_2^+ and O^+. The N_2^+ ions dissociatively recombine very rapidly at low pressures [1] so that their concentration is small. Chemical reactions of O^+ with molecular nitrogen produces NO^+ so that the principal ions which exist below the F_2 peak are O^+, NO^+ and O_2^+. Early flights of a Bennett radiofrequency mass spectrometer made in the auroral zone showed that below 200 km the ions are principally diatomic with O_2^+ being predominant at the lower altitudes [2]. More recently, flights of the same experiment at middle latitudes have shown that of the two molecular ions, NO^+ was predominant below 200 km [3]. In both sets of data, the ion composition measured above 200 km was essentially atomic in nature, mainly O^+. Results from rf spectrometer [4] and ion trap [5] experiments flown on Sputnik III showed that O^+ remains dominant to at least 800 km. In the early reporting of data from a retarding potential experiment flown on the NASA Explorer VIII Satellite [6, 7], it was demonstrated that O^+ predominates at 1000 km in the daytime ionosphere.

In the absence of experimental results, it has been generally believed that at an altitude of approximately 1300 km the ionic composition would change directly from atomic oxygen to protons. One of the important results of the NASA ionospheric physics program has been the conclusion from several experimental observations that an additional transition region must be considered and that there is a "helium layer" interposed between the regions where O^+ and H^+ predominate. Nicolet [8] had previously deduced from observations of drag on the NASA Echo Satellite that neutral helium is an important constituent at very high altitudes. His estimates of the neutral helium number density have since been verified from ground-based optical experiments conducted in the USSR [9].

Even though the discovery of the ionized helium layer is recent, it is already possible to develop a preliminary relationship between the altitude of the transition regions from O^+ to He^+ and from He^+ to H^+ and the atmospheric temperature. Throughout this report, we define the transition altitudes as those altitudes where the ratios O^+/He^+ and He^+/H^+ have a value of unity. Four separate measurements of the lower transition altitude and one of the upper transition altitude are available.

We shall consider first the data from the Explorer VIII retarding-potentia

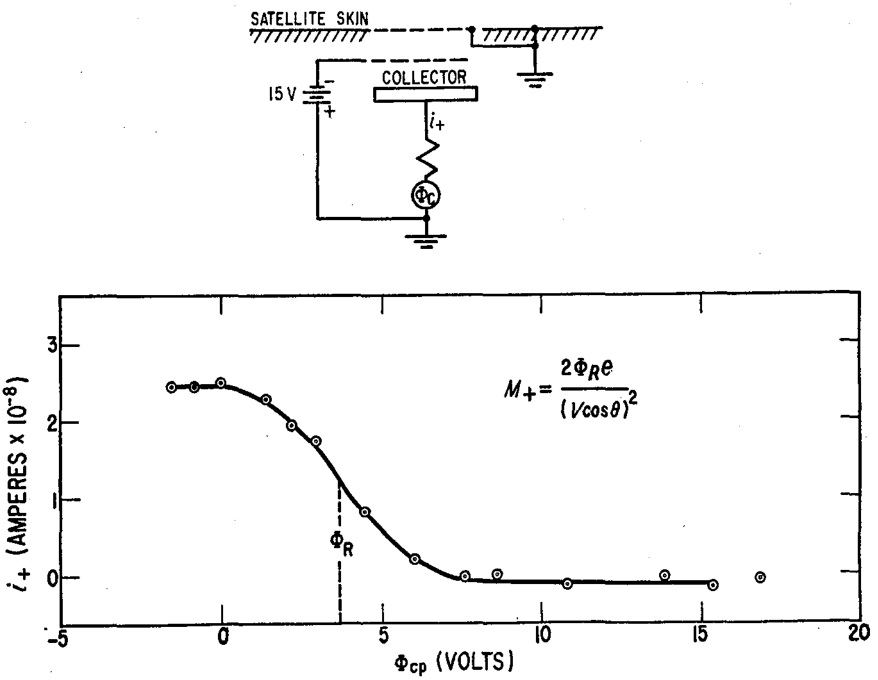

Fig. 1. Results of Explorer VIII regarding potential experiment at an altitude of 1000 km under daytime conditions.

in fig. 1. This experiment is based on the principle that because of the high satellite velocity the ions have a kinetic energy (relative to the vehicle) proportional to their mass. This kinetic energy can be measured from the behavior of the collected ion current as a function of an applied retarding potential. Specifically, the potential of the collector relative to the plasma (ϕ_R) at which one half of the ions of mass M_+ are retarded is given by

$$\phi_R = M_+ (V \cos \theta)^2/2e \tag{1}$$

where V is the satellite velocity, θ is the angle of the sensor relative to the velocity vector and e is the electron charge. To obtain accurate ratios of the ionic constituents the sensor must be pointed in the direction of motion, a condition which, because of the short active life of the satellite, did not prevail except in the altitude region between 700 and 1600 km and then under daytime conditions only. Experimental points for an altitude of 1000 km are shown in fig. 1. The monotonically decreasing nature of the curve is charactersitic of a single ionic constituent which by substitution into eq. (1) of the known satellite velocity and orientation and the value of ϕ_R from fig. 1 is identified as O^+. The abcissa (ϕ_{cp}) in fig. 1 is the collector-

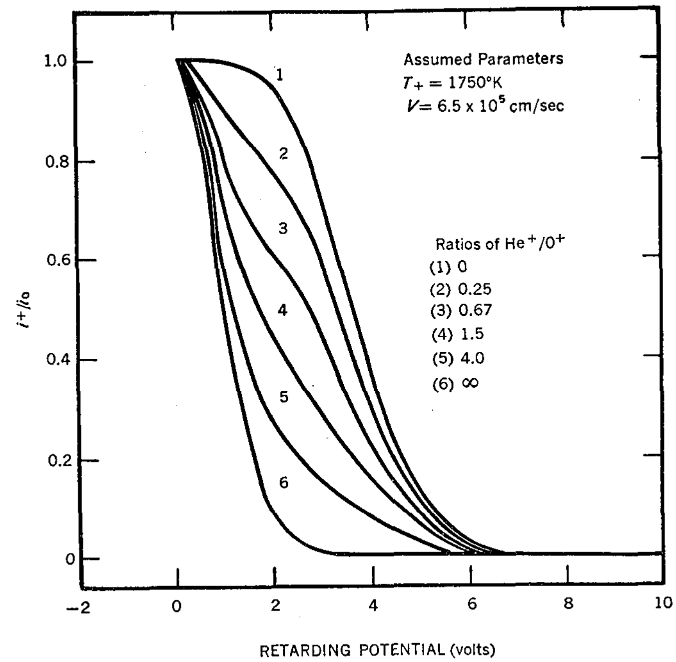

Fig. 2. Theoretical retarding potential curves for a binary mixture of helium and oxygen.

to-plasma potential which is the algebraic sum of the applied collector potential (ϕ_c) and the satellite-to-plasma potential measured separately by a Langmuir probe.

Theoretical retarding-potential curves computed from an expression given by Whipple [10] for binary mixtures of helium and oxygen and for hydrogen and oxygen are presented in figs. 2 and 3. It is seen that an oxygen-helium mixture is characteristically identified by an inflection point and an oxygen-hydrogen mixture by distinguishable plateaus. The shapes of these curves are relatively insensitive to the ion temperature, T_+. Since the Explorer VIII

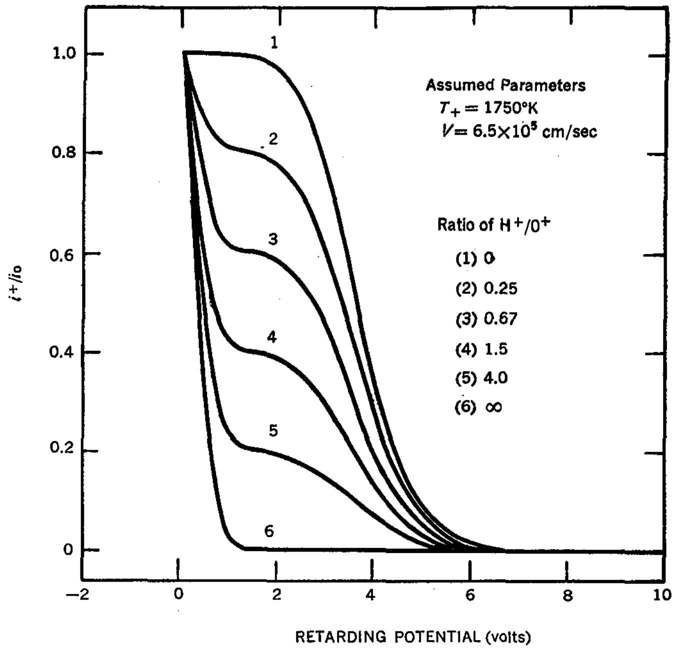

Fig. 3. Theoretical retarding potential curves for a binary mixture of hydrogen and oxygen.

data at altitudes of about 1600 km are characterized by inflection points, it was concluded that the predominant ions at this altitude are O^+ and He^+ [11]. By fitting the experimental points to the family of oxygen-helium curves shown in fig. 3, it was found that the lower transition altitude (O^+ to He^+) was about 1400 km for an atmospheric temperature of approximately 1750 °K.

Hanson [12], who first reported on upper atmosphere helium ions, has indirectly determined both transition altitudes from the changes in scale height of an ion density profile obtained by Hale [13] from an ion trap experiment flown on NASA SCOUT ST–2. The atmospheric temperature derived from the scale height of the electron-ion gas in the region between 1600 and 3400 km on the assumption of a mean ionic mass of 4 AMU was 1600 °K. The transition altitudes from O^+ to He^+ and from He^+ to H^+ which Hanson estimated are 1150 and 3500 km, respectively. Plotted in fig. 4

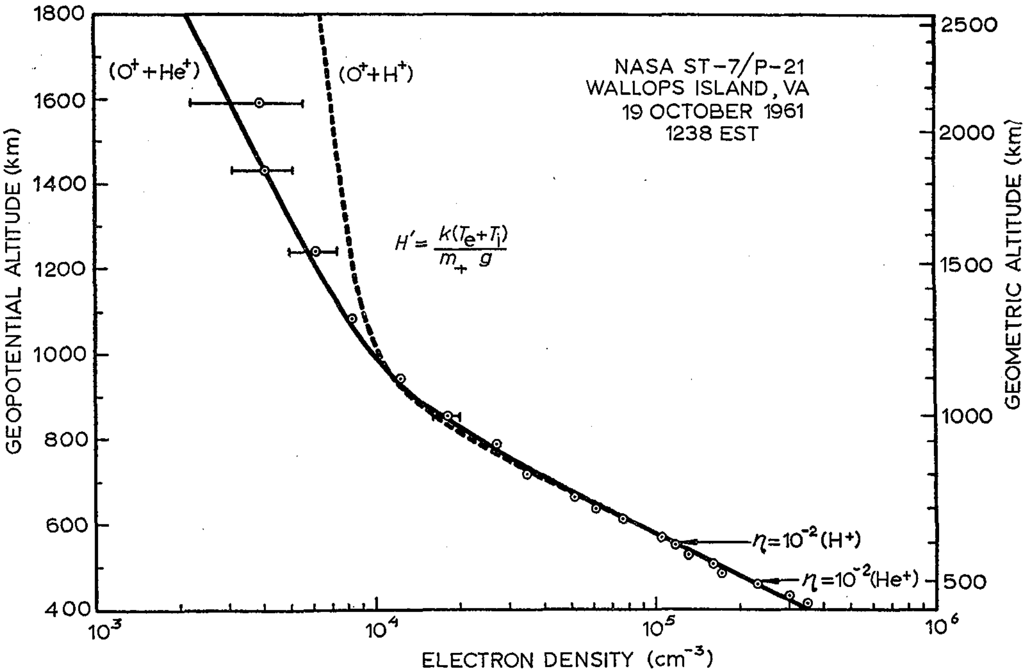

Fig. 4. Comparison of electron density profile obtained by radio propagation experiment with theoretical models.

is an electron density profile obtained by Bauer and Jackson [14] from a radio propagation experiment flown on NASA SCOUT ST–7. The right hand ordinate scale is true or geometric altitude while the left hand scale is geopotential height which takes into account the altitude variation of the acceleration of gravity. As illustrated, the experimental data are more consistent with a transition from O^+ to He^+ (solid line) than from O^+ to H^+ (dashed line). In this case, the inferred atmospheric temperature is 1350 °K and the transition altitude (O^+ to He^+) is 1050 km.

Most recently, Donley [15] has made a direct measurement of He^+/O^+ from a retarding potential experiment flown on NASA SCOUT ST–9 into a nighttime ionosphere. From a preliminary data analysis, the transition altitude appears to be below 800 km at a time when the atmospheric temperature was approximately 750 °K.

The atmospheric temperature dependence of the transition altitudes as determined from Bauer's [16] theoretical expression for the electron density distribution in an isothermal, three-constituent ionosphere in diffusive equilibrium is illustrated in fig. 5. Three curves are shown, two for the upper transition altitude ($H^+ = He^+$) and one for the lower transition altitude ($He^+ = O^+$). For the latter case, the prediction assumes that the ratio He^+/O^+ (η_{21}) has a value of 10^{-2} at 500 km, in accordance with the experimental results of Bauer and Jackson [14]. Plotted on the graph are the four experimental results discussed above, which show reasonably good agreement with the theoretical curve when one considers that the relative concentrations of these ionic constituents may also vary with temperature at the reference altitude.

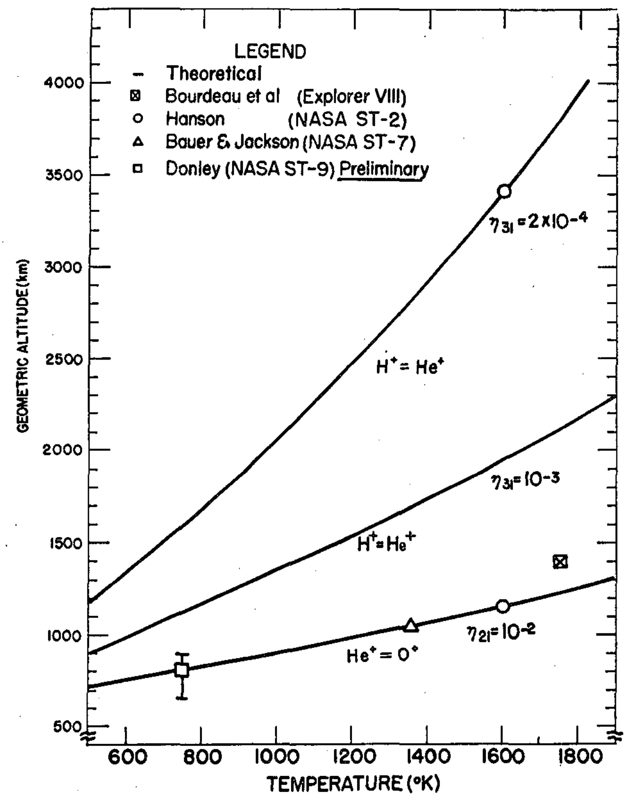

Fig. 5. Ion transition altitude as a function of atmospheric temperature.

The upper theoretical curve assumes that the ratio H^+/O^+ (η_{31}) has a value of 2×10^{-4} at 500 km, a value representative of Hanson's current estimates of proton concentration in the upper ionosphere. The other upper transition altitude curve ($\eta_{31}=10^{-3}$) is inserted to illustrate the radical reduction in the thickness of the helium layer which would result if the relative proton concentration were increased by a factor of five at the reference altitude.

3. Altitude comparison of experimentally-obtained electron temperatures with reference atmospheres

It is of considerable importance to compare electron and neutral gas temperatures since this relationship is dependent upon many parameters essential to the quantitative confirmation of existing theories regarding the formation of the various ionospheric regions. Because direct and indirect measurements of charged particle temperatures have been made under radically different conditions and because of the limitations of the kinetic gas temperature models, various investigators have provided conflicting answers to the important question of temperature equilibrium between electrons and heavy constituents. As this report will show, it is possible to achieve a consistent pattern of the charged particle to neutral gas temperature ratio by careful separation of the reported data with altitude, possibly latitude, and more importantly by treating conditions of quiet and enhanced solar activity as separate cases.

Before proceeding, it is important to define our use of the term "temperature equilibrium". Actually, because in the ionization process the electrons are created with high initial energies, their temperature (T_e) will be higher but will approach that of the kinetic gas (T) asymptotically in time depending on the efficiency of the energy transfer mechanisms. We shall define temperature equilibrium as existing when the difference between T_e and T is smaller than our estimates of the uncertainties in reference atmospheres and in experimental methods of measuring charged particle temperatures. We estimate, perhaps optimistically, that for most cases these uncertainties together are about ten percent of the absolute value of the kinetic gas temperature.

From presently available data, an altitude comparison of electron and kinetic gas temperature is best obtained by comparing Langmuir probe measurements of electron temperatures with recent reference atmospheres. Langmuir probes have required considerable development in order to overcome problems associated with the disturbance introduced into the medium by a conducting body, problems so complex that early results undoubtedly contain first order errors. It was not until 1961 that electron temperatures close to accepted kinetic gas values were first reported for the E region by Japanese investigators [17] and for the upper ionosphere from the NASA Explorer VIII Satellite [18].

In order to perform a valid comparison of electron and kinetic gas temperatures, it is necessary to select electron temperature data representative of

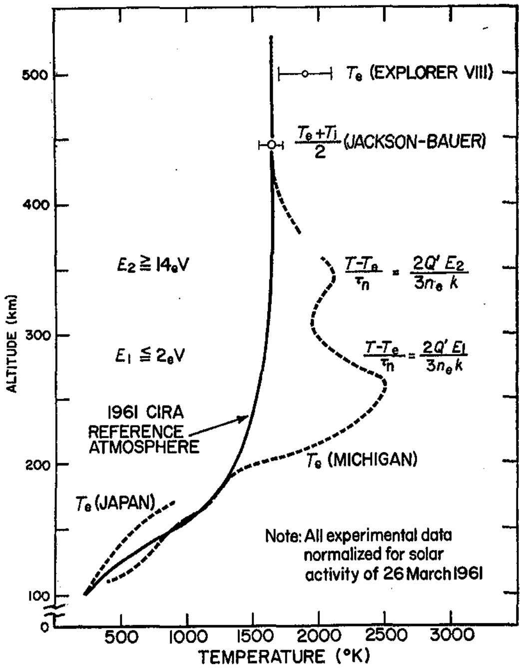

Fig. 6. Comparison of kinetic gas and experimental electron temperatures for quiet *daytime ionosphere at mid-latitudes.*

the characteristic reference atmosphere conditions of a quiet sun at mid-latitudes. Reported electron temperature results from only two rocket flights and one satellite (Explorer VIII) meet these requirements. These data are compared with the 1961 COSPAR International Reference Atmosphere in fig. 6. The rocket Langmuir probe data include the averages obtained by the two probes flown simultaneously by the Japanese and results obtained by the Michigan group using a bipolar probe flown on NASA Rocket 6.04 [19]. All data in the isothermal region, including the reference atmosphere, has been normalized according to Priester's [20] decimeter radiation relationship to the solar activity conditions which prevailed at the diurnal maximum of 26 March 1961, the date of both the Japanese and Michigan rocket flights. Also included on the graph for future discussion is a measurement of the kinetic gas temperature inferred on the basis of temperature equilibrium from a measured electron density profile [21].

When one considers the status of Langmuir probe technology together with the limitations (imposed by the necessity of assuming a neutral composition) of reference atmospheres, the comparison shows good agreement with the hypothesis, based on theoretical considerations of ionizing radiation and energy transfer mechanisms, that temperature equilibrium should be expected in all but the lower F region of the quiet daytime ionosphere [22]. The Japanese data actually show lower electron temperatures than the generally accepted kinetic gas temperatures below 170 km. The Michigan values and the reference atmosphere are virtually identical between 140 and 190 km. Below 140 km, the Michigan group report that their values have larger uncertainties than their other data. When taken together, then, the two sets of rocket data indicate equilibrium between 100 and about 190 km.

In the F region between 200 and 360 km, the Michigan electron temperature values are sufficiently higher than those of the neutral gas that the difference cannot be ascribed to inadequacies of the reference atmosphere or to experimental electron temperature errors. Consequently, this is a definite indication that departure from temperature equilibrium has been established for the F region, with the maximum electron temperature values occurring at about the altitude of maximum absorption of solar radiation.

At apogee of the Michigan flight (360 km) which took place just above the F2 peak, their data show a trend toward a return to temperature equilibrium. As is done in the next section of this report, it can be predicted by quantitative revisions to the Hanson–Johnson hypothesis that the electron and neutral gas become virtually identical at altitudes between 400 and 500 km. This is indicated by the dashed extrapolation of the Michigan results in fig. 6. There are several experimental justifications for temperature equilibrium well above the F2 peak. Explorer VIII data yield electron temperature values which are within 15 percent of the neutral gas models. Although this small indicated departure from equilibrium could be real, it is just as likely that it represent inadequacies in the electron temperature measurements. A second justification is the observation from ground-based radar incoherent backscatter experiments [23], which directly measures the ratio of electron and ion temperature (T_e/T_i), that temperature equilibrium prevails near the F2 peak throughout the day except at sunrise and except for disturbed ionosphere conditions. The third justification comes from the general agreement of temperatures computed from measured scale-heights of the electron-ion gas above the F2 peak and accepted values of neutral gas temperature in the isothermal region. These data are discussed in more detail in a later section. The value by Jackson and Bauer [21] is included in fig. 6 for comparison with the Langmuir probe data.

Since this comparison is for quiet ionospheric conditions at middle latitudes, we have not included results reported by the Michigan group [19] on three other NASA rocket flights, two of which were obtained under disturbed conditions and one in the auroral region. Also excluded are the results of Smith [24] on a NASA rocket flight which took place within 24 hours of the onset of a geomagnetic disturbance. The radar incoherent backscatter results [23] have provided experimental evidence that disturbed ionospheric conditions result in values of T_e/T_i of the order of two.

4. Theoretical considerations of the difference between electron and kinetic gas temperatures

The most recent quantitative theoretical study of the ionospheric electron temperature and its relationship to the kinetic gas temperature was made by Hanson and Johnson [22]. As illustrated in fig. 7, they concluded that

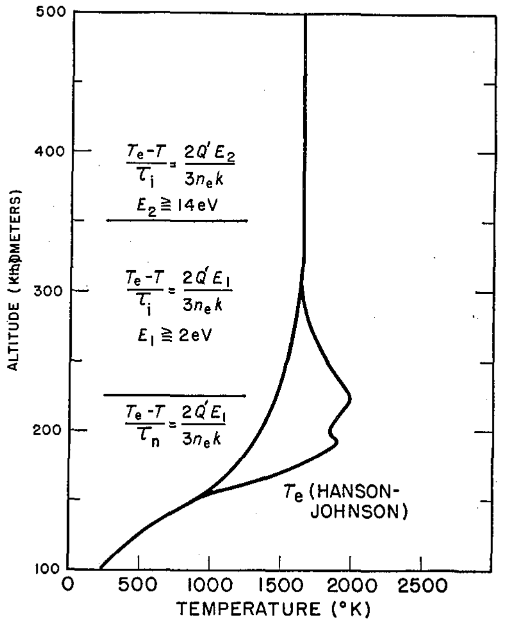

Fig. 7. Theoretical considerations of temperature equilibrium for quiet daytime conditions.

the electron and neutral gas temperatures are virtually identical except at altitudes between 160 and 325 km. In this section we shall summarize their hypotheses and then suggest modifications which are more consistent with the data presented in fig. 6.

Just after ionization has taken place the newly-created photoelectrons, which comprise less than one percent of the total electron population, have energies which exceed that of the neutral gas by at least 14 eV. The process by which this excess energy is transferred to upper atmosphere constituents is an altitude-dependent phenomenon as follows:

(a) *Below 225 km*, inelastic collisions with neutral particles reduce the photoelectron energy to 2 eV, the cutoff point of the excitation cross-section of atomic oxygen. The 2 eV electrons then share their energy with the ambient electrons, thus raising their temperature above that of the heavy constituents. This process is very fast so that the electrons have a Maxwellian energy distribution, a conclusion which has been verified experimentally by the shapes of the volt-ampere curves of those Langmuir probes whose potentials are permitted to reach plasma potential.

After a Maxwellian distribution of electron energy is established, the temperature difference is calculated by relating the heat input to the electrons to the heat lost by elastic collisions with heavy particles:

$$\frac{2Q'\ (E_1)}{3N_e\,k} = \frac{T_e - T}{\tau_n}, \quad z < 225 \text{ km}, \tag{2}$$

where Q' is the rate at which photoelectrons of energy E_1 (2 eV or less for this case) are released, N_e is the electron density, k is Boltzmann's constant, and (τ_n) is the time which it takes for electrons of energy E_1 to transfer their excess energies to neutral particles.

(b) *Between 225 and* 350 *km*, the process is the same except that the time which it takes for 2 eV electrons to transfer their excess energies to ions (τ_i) is shorter than (τ_n) so that

$$\frac{2Q'\ (E_1)}{2N_e\,k} = \frac{T_e - T}{\tau_i}, \quad 225 \text{ km} < z < 350 \text{ km} \tag{3}$$

(c) *Above 350 km*, the inelastic collision process is no longer efficient so that the photoelectrons transfer their energy directly to the ambient electrons, raising the value of E_1 to E_2, which is 14 eV or larger depending upon whether one or two photoelectrons are released per incoming photon:

$$\frac{2Q'\ (E_2)}{3N_e\,k} = \frac{T_e - T}{\tau_i}, \quad z > 350 \text{ km}. \tag{4}$$

Hanson and Johnson calculated from available atmospheric models that temperature equilibrium as we have defined it would prevail except between 160 and 325 km, a region where high solar radiation absorption is accompanied by moderate values for the respective equipartition times. The principal uncertainties in their computations result from corresponding uncertainties in cross-sections and densities of the atmospheric constituents. They noted in proof that an overestimate of the excitation cross-section of atomic oxygen caused them to overestimate the altitude at which inelastic collisions are no longer effective and we note below that this radically affects the altitude domains in which the various energy transfer mechanisms come into play. The rearrangement offers one explanation for the experimental results presented in fig. 6.

The major effect of lowering the altitude above which inelastic collisions are no longer important is that the efficiency of energy transfer by elastic collisions with ions is greatly reduced. If we must consider equipartition times (τ_i) based on electrons with energies of 14 eV or greater rather than 2 eV at all altitudes, we estimate that energy transfer to ions does not control the electron temperature below about 600 km.

Following this reasoning, we must now consider two altitude domains below 600 km, an upper portion where energetic electrons of 14 eV or greater transfer their energy directly to the ambient electrons and a lower portion where because of the intervening inelastic collision process there are only 2 eV available for selective electron heating. In both domains the temperature difference $(T_e - T)$ is finally controlled by elastic collisions with neutral constituents.

In order to provide new estimates of $T_e - T$ at all altitudes, we have calculated $(Q'E)$ from eq. (2), using $T_e - T$ values from fig. 6 in the altitude region where the difference is measurable (200–360 km), equilibration times (τ_n) in accordance with Hanson and Johnson, and electron densities measured during the Michigan flight by an ionosonde and by a rocket-borne propagation experiment. We note in these calculations that at 325 km a discontinuity appears in the $Q'E$ function. This discontinuity may be attributed to the transition altitude where inelastic collisions are no longer efficient. As a consequence, above this altitude more energy is available for selective electron heating and the secondary maximum in the Michigan electron temperature profile in the 300–350 km region may possibly be explained in this fashion. The new equations which seem to apply below and above 325 km are included as part of fig. 6.

By an extrapolation of the $Q'E$ function, of the values of τ_n given by Hanson and Johnson (which are now reduced above 325 km), and of the electron density profile, we conclude for the ionospheric conditions representative of fig. 6 that the electron and kinetic gas temperatures are virtually identical below about 190 and above about 450 km. Below 190 km, the justification is the reduction of photoelectron energy by inelastic collisions together with high collision frequencies. In the higher altitude region, it appears that the heat input to the electrons is decreasing more rapidly with altitude than the combined effect of an increasing equipartition time and a decreasing electron density. This does require a somewhat more rapid decrease in $Q'E$ at the higher altitudes than what would be inferred from a recent study by Watanabe and Hinteregger [25] but, as they point out, their analysis is only a first approximation which can be refined as the atmospheric composition and some photoionization and absorption cross-sections become better known.

5. Diurnal and solar activity variation of upper ionosphere temperatures

Above 200 km, neutral gas temperatures are generally derived from atmospheric densities computed from satellite drag observations and an assumed atmospheric composition. The drag observations show that density variations are correlated with solar activity. Although not the source of upper atmosphere heating, solar decimeter radiation which is observable at the earth surface is an indicator of this interrelationship. Different empirical equations which relate 10.7 and 20 cm solar radiation and atmospheric temperature in the isothermal altitude region have been derived by Jacchia [26] and Priester [30]. Jacchia's equations are based on an atmospheric model of Nicolet [27] which includes the presence of helium and where the mean molecular weight is computed on the basis of diffusive equilibrium of the atmospheric constituents. Priester's model, on the other hand, makes use of a molecular mass variation typical of the 1961 CIRA reference atmosphere.

Theories of upper atmospheric heating can be enhanced by comparing such models of the diurnal and solar activity variations of neutral gas temperatures with charged particle temperatures obtained in the isothermal altitude region. To do so, it is necessary to assume temperature equilibrium well above the F2 peak, an assumption which was justified theoretically and experimentally in the previous sections.

One method of deducing charged particle temperatures above the F2 peak is to measure accurately the electron or ion density profile. From theoretical considerations as well as experimental evidence, it is now well established that the distribution of electrons and ions at these altitudes generally corresponds to a diffusive equilibrium distribution. One such experimental evidence, a daytime electron profile measured by a radio-propagation method [21], is illustrated in fig. 8. In such cases, the slope of the charged particle distribution is a unique measure of the scale height

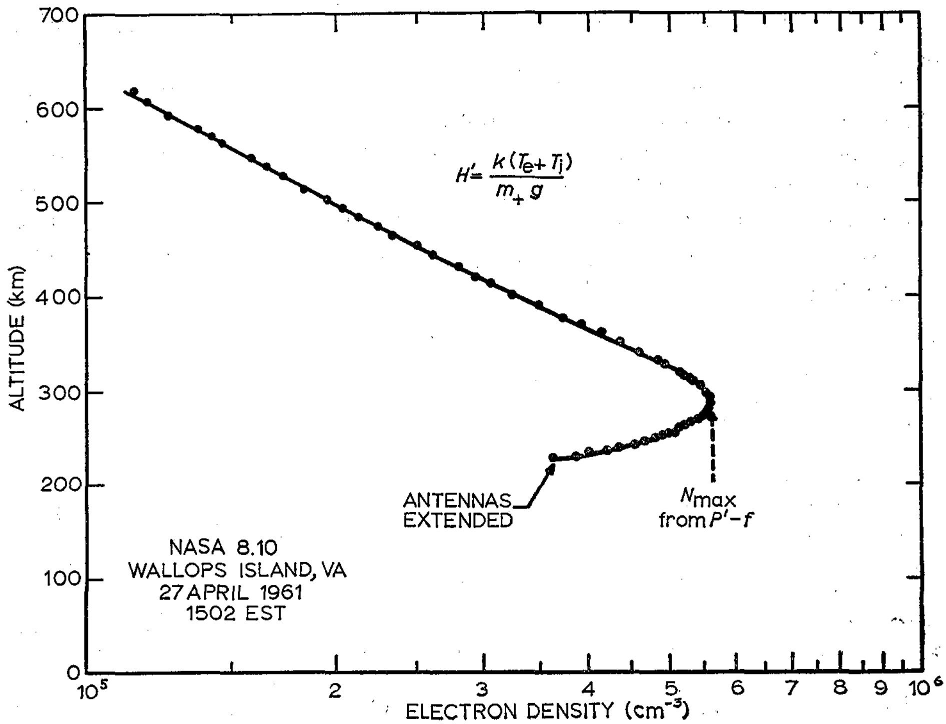

Fig. 8. Electron density profile from radio-propagation experiment illustrating isothermality of upper ionosphere.

of the electron-ion gas and for regions where one ionic constituent predominates it is also a measure of the sum of the electron and ion (T_i) temperatures. In general, the scale-height of the electron-ion gas is given by

$$H' = \frac{k(T_e + T_i)}{m_+ g} = \left[\frac{d}{dz}(\ln N)\right]^{-1} \tag{5}$$

where m_+ is the mean ionic mass, g is the acceleration of gravity, N is the charged particle density and z the altitude. Thus H' is a measure of $T_e + T_i$ or in the case of temperature equilibrium of the neutral gas temperature, $T = (T_e + T_i)/2$.

Parenthetically, the high degree of isothermality in T_e+T_i evidenced by the fig. 8 experimental results provides additional support for temperature equilibrium well above the F2 peak. For this to occur with radical differences between T_e and T_i requires the rather unlikely possibility that the energy input to the electrons ($Q'E$) is decreasing with altitude identically as the combined rate of increase in equipartition time and of decrease in electron density.

Six rocket measurements of the altitude profile of charged particle densities above the F2 peak have been reported during the last year. In addition to those presented in fig. 3 and 7, two electron density profiles were obtained from the NASA topside sounder program [28], and the remaining two are ion density profiles. The six sets of data are listed in the following table along with the kinetic gas temperature inferred from an assumption of temperature equilibrium.

TABLE 1

Rocket measurements of atmospheric temperature above the F2 peak

Identification	Local time (h)	Temperature (°K)	Source
NASA ST–7	1238	1350 ± 100	Bauer & Jackson [14]
NASA ST–2	1500	1600 ± 100	Hanson [12]
NASA 8.10	1502	1640 ± 90	Jackson & Bauer [21]
NASA 8.15	1812	1200 ± 60	Jackson *et al.* [28]
NASA 8.04	2044	1240 ± 70	Hanson & McKibbin [29]
NASA 8.17	2326	800 ± 40	Jackson *et al.* [28]

In fig. 9 are plotted the Jacchia (dashed lines) and Priester (solid lines) models of the atmospheric temperature in the isothermal altitude regions as a function of solar decimeter radiation flux. For comparison, the temperatures from the above table are located on the graph in accordance with the solar decimeter radiation observed on the individual launch dates. Also included is a direct measurement of the neutral gas temperature obtained by Blamont [30] from a sodium release experiment flown on NASA Rocket 8.05. It is important to note that the rocket data have not been normalized for diurnal time.

Blamont's value of 1475 ± 40 °K, which was obtained at local sunset, is higher than Jacchia's diurnal maximum value, indicating that the latter's daytime temperatures are too low. One value of $(T_e+T_i)/2$ obtained by a topside sounder experiment (NASA 8.15) is in very good agreement with Blamont in that it also was taken at local sunset and it too is higher than Jacchia's diurnal maximum curve. Three of the rocket measurements of

$(T_e+T_i)/2$ were taken within two hours of the diurnal maximum. All three are consistent with Blamont's data in that they are higher than Jacchia's model but lower than or equal to Priester's values for the diurnal maximum. The remaining measurements of $(T_e+T_i)/2$ are for nighttime conditions. One which was taken close to midnight (NASA 8.17) agrees quite well with both Jacchia's and Priester's diurnal minimum. This should be expected since

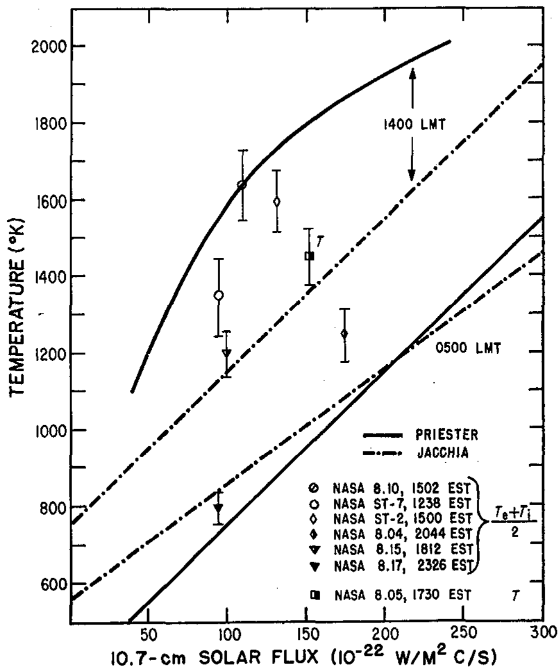

Fig. 9. Upper ionosphere temperature as a functon of solar activity.

not much cooling will occur between midnight and the diurnal minimum. The other nighttime value (NASA 8.04) was taken about two hours after sunset when the atmosphere is cooling toward diurnal minimum. As expected, this value falls between the diurnal maximum and minimum values.

Considering that both Jacchia and Priester's kinetic gas temperatures are an inferred rather than a measured parameter, the general agreement of the various charged particle measurements with their temperature models is reasonably good. It appears from the daytime values of temperatures deduced from charged particle observations as well as from Blamont's direct measurement of neutral gas temperature that the diurnal variation of temperature in the isothermal region is closer to 80 percent suggested by Priester than 35 percent suggested by Jacchia.

Inasmuch as the rocket measurements are in somewhat closer agreement with Priester's model, they are plotted in fig. 10 as a function of local mean

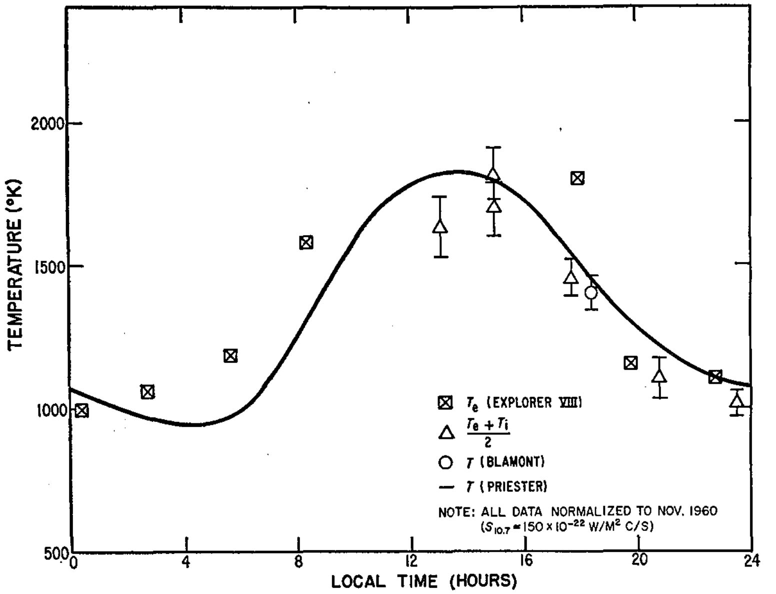

Fig. 10. Diurnal variation of upper ionosphere temperatures.

time to further illustrate the agreement with his implied diurnal variation [31]. Electron temperatures reported from the Explorer VIII Satellite are also included. All data have been normalized to the average 10.7 cm flux for the month of November 1960. It should be emphasized that the individual electron temperature values from Explorer VIII have a 200 °K error spread which is not indicated on the graph. Assuming temperature equilibrium, it would appear from the Explorer VIII data that Priester's daytime values are too low. However, there is a possibility of second-order errors in these Langmuir probe measurements of electron temperature [32]. There is fair agreement between indirect measurements of charged particle temperatures and Priester's values with a possible implication that the diurnal maximum is broader than indicated.

6. Variability extremes of electron densities in the upper ionosphere

It has been brought out indirectly in the preceeding section that electron densities in the upper ionosphere are controlled by the atmospheric temperature and ion composition. They are, of course, additionally controlled by $N_{\max}$ values at the F2 peak, which are in turn governed by absorption of solar radiation and by recombination processes occurring in the lower F region. In this section, we plan to illustrate the variability extremes which these factors produce in upper ionosphere electron densities by comparing ionosonde data with electron density measurements by Kane [33] using a radio-frequency probe experiment flown on the Explorer VIII Satellite.

In fig. 11 are plotted the extreme theoretical electron density profiles which, assuming diffusive and temperature equilibrium, would be expected

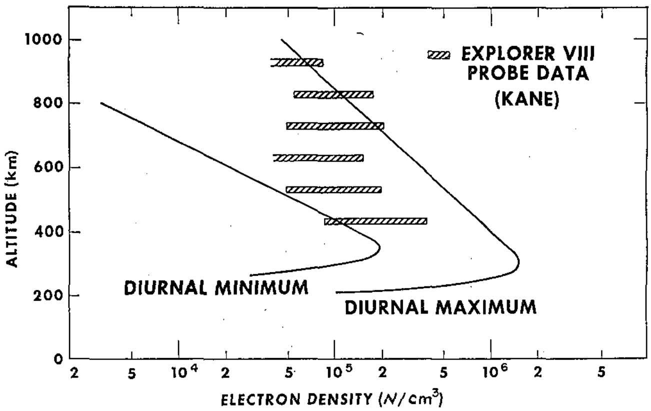

Fig. 11. Comparison of electron densities from Explorer VIII Satellite of impedance probe with theoretical models.

during the active life of the Explorer VIII Satellite, using observed ionosonde data for $N_{\max}$ values and the diurnal variation of atmospheric temperature prevailing at that time. The shaded areas indicate the variability of electron densities observed by the rf impedance probe. Each segment plotted at the nearest 100 km level represents about 50 data points.

The rf probe experiment, which was originally developed by Jackson and Kane [34], depends upon a comparison of the in-flight capacitance (C) of a shortened dipole antenna to the latter's free space value (C_0) at a radio frequency f. The electron density is computed from the simplified Appleton–Hartree formula which relates N_e to the dielectric constant (K) of the medium as follows:

$$K = \frac{C}{C_0} = 1 - \frac{81 N_e}{f^2}, \tag{6}$$

where f is in kilocycles.

The principal uncertainty in the measurement is due to the ion sheath which forms about the antenna, an error which can be estimated from a knowledge of the potential which the spacecraft acquires relative to the medium [35]. In the case of Explorer VIII where satellite potentials varied between approximately zero for daytime conditions up to -1 volt at night, Kane estimates that the uncertainties due to the ion sheath corresponds to electron densities of the order of $2 \times 10^4 N/\text{cm}^3$. For this reason, values below $4 \times 10^4 N/\text{cm}^3$ were not considered in the data recorded in fig. 11.

It was observed that whenever the satellite was within one degree of latitude and longitude at perigee (425 km) of an ionosonde that the electron density observed on the satellite was consistent with what would be expected from the $N_{\max}$ value. It was noted on some perigee transits which occurred near local midnight that fluctuations in the electron density were less than 10 percent over a distance of the order of 500 km along the direction of the satellite orbit.

As would be expected, the experimental values at the lower altitudes which were taken at night are closer to the theoretical diurnal minimum curve. We attribute the values which exceed the model above 700 km to the fact that in this region the satellite was passing either into a sunrise or sunset condition and in this case diffusive and probably temperature equilibrium may not apply.

7. Acknowledgment

The authors are indebted to J. L. Donley and J. A. Kane of the Goddard Space Flight Center for the use of their retarding potential and rf probe data, respectively.

References

1. A. C. Faire and K. S. Champion, Phys. Rev. 113 (1959) 1–6
2. C. Y. Johnson, E. B. Meadows and J. C. Holmes, J. Geophys. Res. 63 (1958) 443–444
3. H. A. Taylor Jr and H. C. Brinton, J. Geophys. Res. 66 (1961) 2587–2588
4. V. G. Istomin, Artificial Earth Satellites, 2 (1962)
5. V. I. Krassovsky, Proc. IRE, 41 (1959) 289–295
6. R. E. Bourdeau, Space Research II, ed. H. C. van de Hulst *et al.* (Amsterdam, North-Holland Publishing Company 1961)
7. R. E. Bourdeau, J. L. Donley and E. C. Whipple, Jr., NASA Tech. Note D–414 (1961) National IAS-ARS Symposium (June 1961)
8. M. Nicolet, J. Geophys. Res. 66 (1961) 2263–2264
9. N. N. Shefov, Ann. de geophysique, 17 (1961) 395–402
10. E. C. Whipple Jr., Proc. IRE, 47 (1959) 2023–2024

11. R. E. Bourdeau, J. L. Donley, E. C. Whipple Jr. and S. J. Bauer, J. Geophys Res. **67** (1962) 467–475
12. W. B. Hanson, J. Geophys. Res. **67** (1962) 183–188
13. L. C. Hale, Abstract, J. Geophys. Res. **66** (1961) 1554
14. S. J. Bauer and J. E. Jackson, J. Geophys. Res. **67** (April 1962)
15. J. L. Donley, private communication (1962)
16. S. J. Bauer, J. Atms. Sci., **19** (1962) 276–278
17. Y. Aono, K. Hirao and S. Miyazaki, J. of the Radio Research Laboratories **8** (1961) 453–465
18. G. P. Serbu, R. E. Bourdeau and J. L. Donley, J. Geophys. Res. **66** (1961) 4313
19. N. W. Spencer, L. H. Brace and G. R. Carignan, J. Geophys. Res. **67** (1962) 157–175
20. W. Priester, J. Geophys. Res. **66** (1961) 4143–4148
21. J. E. Jackson and S. J. Bauer, J. Geophys. Res. **66** (1961) 3055–3057
22. W. B. Hanson and F. S. Johnson, Les Congrès et Colloques de l'Université de Liège, *20* (1961) 390–424
23. K. L. Bowles, G. R. Ochs and J. L. Green, NBS J. of Res., Section D, in press (1962)
24. L. G. Smith, "Electron density measurements by the asymmetric probe," presented to AGU (April 1961)
25. K. Watanabe and H. A. Hinteregger, J. Geophys. Res. **67** (1962) 99–1006
26. L. G. Jacchia, Nature, **192** (1961) 1147–1148
27. M. Nicolet, Spec. Rept. No. 75, Smithsonian Institution (1961)
28. J. E. Jackson, R. W. Knecht and S. Russell, "First results in NASA topside sounder program," Proc. 8th Annual Meeting of the American Astronaut. Sci., in press, (1962)
29. W. B. Hanson and D. D. McKibbin, J. Geophys. Res. **66** (1961) 1667–1671
30. J. Blamont, Space Research II, ed. H. C. van de Hulst *et al.* (Amsterdam, North-Holland Publishing Company 1961)
31. R. Jastrow, 25th Wright Brothers Lecture (Dec. 1961)
32. R. E. Bourdeau, J. L. Donley, G. P. Serbu and E. C. Whipple Jr., J. Astron. Sci. 8 (1961) 65–73
33. J. A. Kane, private communication (1962)
34. J. E. Jackson and J. A. Kane, J. Geophys. Res. **64** (1959) 1074–1075
35. J. A. Kane, J. E. Jackson and H. A. Whale, NASA Technical Note D–1098 (1962)

PRINTED IN THE NETHERLANDS