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Research within the Ionosphere

We have revised our understanding of this atmospheric region by using remotely controlled laboratories.

Robert E. Bourdeau

Our understanding of the mechanisms which govern the characteristics of the earth's ionosphere has been recently enriched by rocket and satellite observations and by the results of new types of ground-based experiments.

Traditionally, the ionosphere is defined as that portion of the upper atmosphere which contains a significant number of charged particles with thermal energies (up to a few tenths of an electron volt). These charged particles, electrons and ions, result from ionization of the neutral constituents of the ionosphere by ultraviolet and x-radiation from the sun, and possibly by corpuscular radiation. The electrons are lost by recombination with the positive ions that are simultaneously produced. The rate of loss is low, and thus the ionosphere persists throughout the night, especially at the higher altitudes. Because of the high number density of the electrons, the ionosphere classically is associated with its effects on radio communication.

In addition to these mechanisms of production and loss, gravitational and electromagnetic forces contribute to the characteristics of the ionosphere. As a result of these various factors, several regions with unique features are formed. These are known as the D region (50 to 85 km above the earth), the E region (85 to 140 km), the F region (140 to 600 km), and the upper ionosphere (600 km to several earth radii).

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The D region, the E region, and that portion of the F region which lies below about 300 kilometers were identified and named as a result of research with the ground-based ionosonde, the classical tool of ionospheric research. With this "low-frequency radar" one measures the time interval between transmission of a radio signal from the earth and reception of the echo reflected from the ionosphere. The electron density at the point of reflection is proportional to the square of the frequency. Therefore, when this time interval is measured as a function of frequency it is possible to obtain a value for electron density as a function of altitude. We have learned much about the variations, with time and latitude, in the distribution of electrons in the lower ionosphere through long-term world-wide use of the ionosonde.

It is the purpose of this article to summarize recent advances in our understanding of the ionosphere, with emphasis on those made as a result of our new ability to place observatories in the medium under study. Such advances involve a relating of the variation, with altitude, latitude, and time, of all characteristics of the charged particles to gravitational and electromagnetic forces, to possible ionizing sources, and to the nature of the neutral atmosphere from which the ions and electrons are created.

The Neutral Atmosphere

The neutral atmosphere classically is divided into regions in accordance with the variation of temperature with altitude. The altitude dependence of temperature is represented for average daytime conditions (*1*) in Fig. 1 (left). Free electrons are found in significant abundance only above 50 kilometers. Consequently, the regions of the neutral atmosphere that are of major interest to the investigator of the ionosphere are the mesosphere, which lies between the temperature maximum at 50 kilometers and the minimum near 85 kilometers, and the thermosphere (above 85 km).

Mesospheric temperatures have been deduced principally from rocket-borne pressure gages and by sound-velocity experiments made by means of rocket-borne grenades. The data show that the mesosphere exhibits large variations with changes of latitude and season (*2*). The large increase in temperature in the lower thermosphere is due principally to the absorption of ultraviolet radiation from the sun. Heat conduction keeps the temperature nearly constant above 200 kilometers (*3*). Thermospheric temperatures have been deduced mainly from measurements of atmospheric density that were made by means of gages flown on rockets (*4*) and satellites (*5, 6*) and indirectly through study of the shrinking of satellite orbits (*7*).

From the standpoint of theory about formation of the ionosphere, the most important parameter of the neutral atmosphere is its composition. In Fig. 1 (right) an average percentage distribution of the major constituents is presented (*1*) as a function of altitude. Below 100 kilometers mixing controls the relative abundances of the neutral constituents, and consequently molecular oxygen and nitrogen predominate. Above this altitude, dissociation of atomic oxygen takes place as a result of the absorption of ultraviolet radiation by O_2. At the higher altitude mixing becomes unimportant and the constituents are in diffusive equilibrium, each component being distributed independently of the others. The distribution of the constituents can be

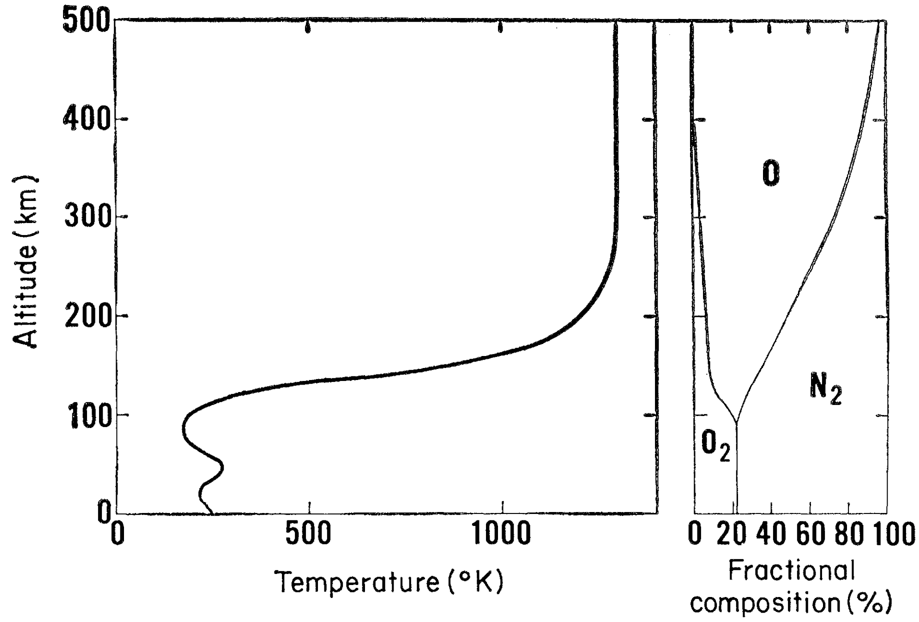

Fig. 1. Dependence on altitude of the temperature and composition of neutral gas in the ionosphere. [From Johnson (*1*)]

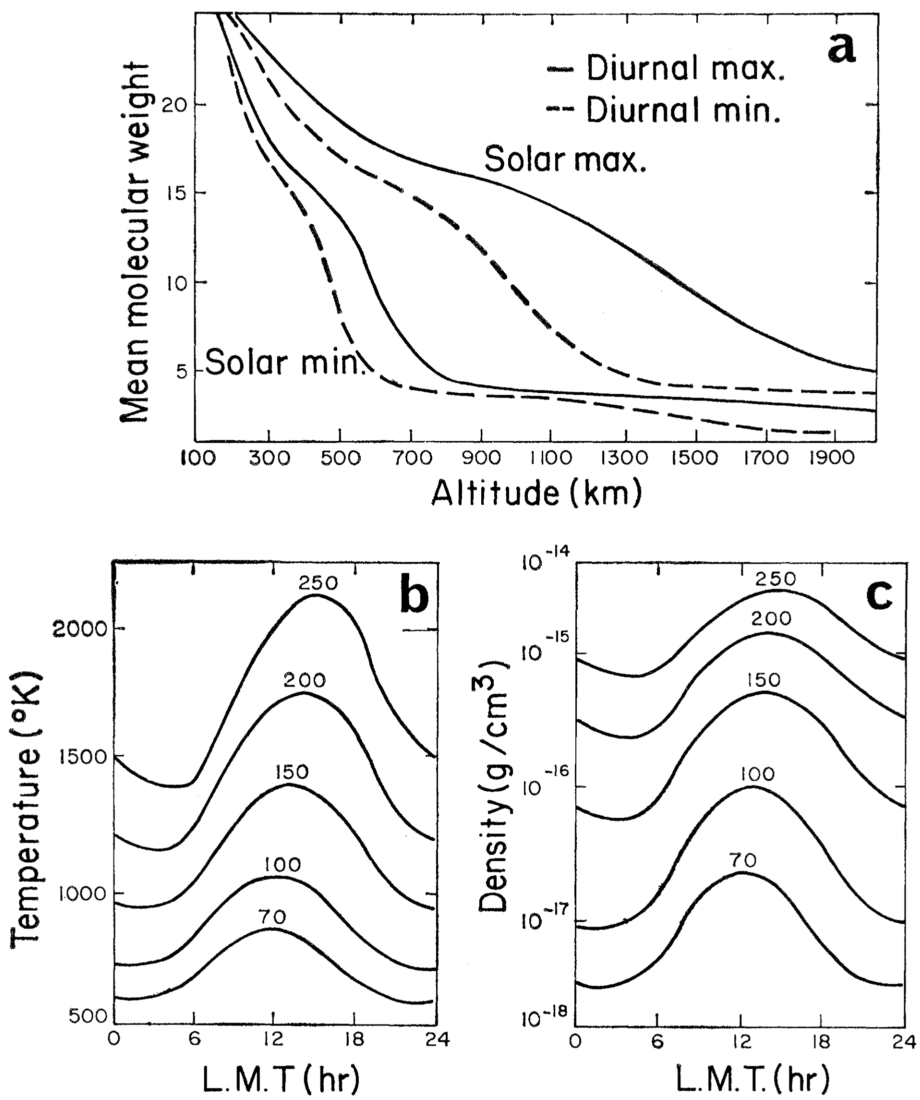

Fig. 2. Models of variations, with time and solar flux, of properties of ionospheric neutral gas: variation of (*a*) mean molecular weight, (*b*) temperature of neutral gas in the thermosphere, (*c*) density at altitude of 600 kilometers. *LMT*, Local mean time. [From Harris and Priester (*12*)]

calculated theoretically from the hydrostatic equation, assumed values being used for the altitude at which diffusive separation occurs and for atmospheric temperatures.

In Fig. 1 (right) it may be seen that the molecular constituents diminish in importance with increasing altitude, so that atomic oxygen dominates the atmosphere at 500 kilometers. Above 500 kilometers the lighter gases become important. Up until the time an analysis of atmospheric drag on the Echo 1 satellite was made it had been believed that there was a direct transition from an atmosphere of oxygen to one of hydrogen. However, that analysis (*8*) first suggested the existence of an intervening helium layer. The existence of neutral helium at the higher altitudes was confirmed (*6*) by mass spectroscopy aboard the Explorer 17 satellite, some time after ionized helium had been detected from rocket (*9*) and satellite (*10*) experiments. The thickness and altitude of the helium region should be strongly dependent on the atmospheric temperature (*11*). This effect is reflected in graphs (Fig. 2*a*) of mean molecular weight as a function of altitude for extremes of the diurnal and solar cycle (*12*). The region is believed to be diminishingly thin—for example, it disappears at night throughout the year of minimum solar activity.

The structural behavior of the atmosphere that is shown in Figs. 1 (right) and 2*a* has been inferred principally from total density measurements obtained by means of rocket-borne gages and from analyses of satellite drag. Early rocket-borne mass spectrometers (*13*) gave qualitative evidence that diffusive equilibrium controls the composition of the atmosphere at the higher altitudes. However, in the early experiments the probability of error was high because instrumental inadequacies caused the gas under study to be changed from its ambient state before it entered the analyzer section of the instrument. It is only in the last year that quantitatively significant measurements of the O/O_2 and O/N_2 ratios have been obtained by direct sampling (*6, 14*).

Observations of satellite drag show that the temperature and density of the isothermal region of the thermosphere vary considerably with time of day and with the 11-year solar cycle (Fig. 2, *b* and *c*). The five temperature and density curves (*12*) of Fig. 2, *b* and *c*, are for different levels of solar activity; an index of this activity is the intensity

(S) of radio noise measured at the earth's surface. The S value for the five curves ranges from 70 at sunspot minimum to 250×10^{-22} watt per square meter per cycle per second during the year of maximum solar activity.

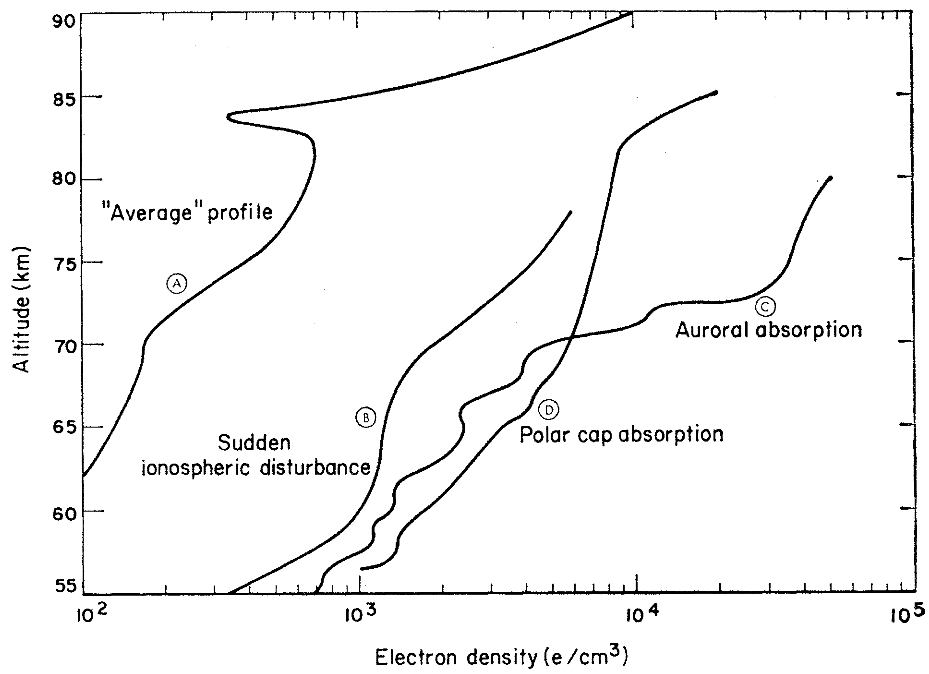

Fig. 3. Electron density profiles for the D region of the ionosphere.

The Normal D Region

The D region, which occupies approximately the same altitude interval as the mesosphere (50 to 85 km), is the lowest region where free electrons are found in significant number. Here, the relatively dense atmosphere results in a high frequency of collisions between the electrons and the neutral constituents. There is a high probability that electromagnetic energy which has been transferred to the electrons will be lost irretrievably in these collisions. Thus, the D region acts as an absorber of radio waves and, from the standpoint of radio communication, is the most important subdivision of the ionosphere. Yet it is the least studied experimentally, primarily because of two factors: (i) the difficulty of devising experiments which are valid in such a weakly ionized medium, and (ii) the tendency of most investigators to perform the more esoteric satellite experiments in the upper ionosphere.

In this section I discuss only the "normal" D region, limiting the theoretical conditions geographically to midlatitudes and temporally to times when there are no solar-flare effects. It is only quite recently that even a preliminary model for the distribution, with altitude, of electrons in the normal D region has been proposed, despite the fact that the region is within the range of relatively inexpensive rockets.

The abundance of free electrons in the normal D region is too low to permit study by means of the conventional ground-based ionosondes. However, breakthroughs have been achieved as a result of the development of more complex ground-based radio propagation experiments (*15, 16*). One common denominator of ground-based methods is the fact that the altitude dependence of electron density (N_e) is extracted from the data only through assuming a profile for frequency of collision (ν) of the electrons, since both N_e and ν simultaneously affect the measured radio-wave phenomena. On the other hand, a collaborative effort on the part of a team of investigators, some from the Goddard Space Flight Center and some from Scandinavia (*17, 18*), has resulted in novel and complex experiments, involving transmission of radio signals from the ground to rocket-borne receivers, in which the *in situ* reception permits separation of N_e and ν with sensitivity adequate for studying the low electron densities found in the normal D region.

In Fig. 3 the few available rocket and ground-based observations have been combined to generate an average N_e profile for the normal daytime D region (curve A). This profile is only one of the important pieces of information required to explain how the region is formed. To complete the task one must relate N_e to the competition between electron production and electron loss for each discrete altitude.

The rate of electron production (q) can be computed from a knowledge of (i) the intensity of the ionizing radiation, (ii) the density of the ionizable constituents responsive to this radiation, and (iii) the absorption cross sections of the ionizable constituents. The problem of estimating q is complex because the cross section for each individual constituent is a different function of wavelength if solar radiation is the ionizing source, or of electron or proton energy if corpuscular radiation is the source.

Electron loss in the D region is believed to occur mainly through dissociative recombination of electrons with positive ions, a process which leads to the formation of an excited but neutral constituent. To estimate the rate of electron loss requires a knowledge of the rates of recombination, which are different for the various ion species.

As a result mainly of rocket measurements of solar radiation, theoretical models (*19*) narrow the possible sources of ionization of the normal D region to three, which may act singly or in combination. The view that ionization of the lower part of the region (between 50 and 70 km) is produced by the action of cosmic rays on the principal neutral constituents (O_2 and N_2) is generally accepted. If this is indeed the case, the degree of ionization in this lower part of the D region should show a strong latitude dependence. There is some disagreement as to the relative roles of the other two possible sources in ionizing the upper part of the D region. One possibility is ionization of O_2 and N_2 by x-rays of 2- to 8-angstrom wavelength—an extremely variable source with a very low intensity (not exceeding 10^{-3} erg cm^{-3} sec^{-1} at times of solar inactivity). The other possibility is Lyman alpha radiation (1216 angstroms), the only ultraviolet radiation which has a favorable absorption cross section and which, in rocket tests, has been observed to penetrate into the D region. This stable but intense radiation, measurable in a few ergs per cubic centimeter per second, acts only upon a trace constituent, nitric oxide. Rocket and satellite measurements indicate that the x-ray fluxes at the extremes of the solar cycle vary by more than two orders of magnitude

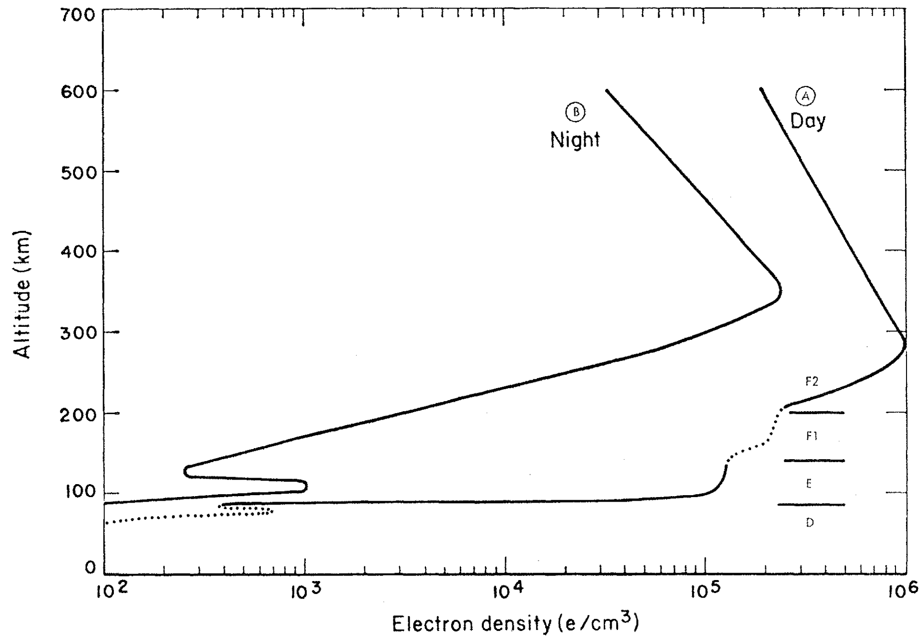

Fig. 4. Typical electron density profiles for the D, E, and F regions of the ionosphere.

(*20*). Therefore, the relative importance of x-rays and Lyman alpha radiation in the formation of the normal D region depends on the level of solar activity.

In only a few space-flight experiments have the ionization source and the ionization characteristics been simultaneously measured. According to some observers (*17*) who measured N_e and Lyman alpha flux simultaneously in a rocket experiment, x-radiation can be ruled out as a significant source of ionization of the normal D region, at least for the year of minimum solar activity. To be certain of the relative importance of x-ray and Lyman alpha flux at all times, we badly need laboratory investigations to resolve existing uncertainties about absorption cross section and recombination rates.

An important tool in ionospheric research is the ion spectrometer. Making observations with this instrument in the D region is very difficult—so difficult that it has been accomplished only once (*21*), and this during the past year. Other than possible contaminants borne aloft by the rocket, the major ionic constituent observed below 83 kilometers was NO^+. This observation supports the Lyman alpha hypothesis but does not rule out, a priori, ionization by x-radiation, because of the possibility of ion-molecule interaction (*22*). For example, O_2^+ produced directly by x-rays can react with an N_2 molecule to form an NO^+ ion and an NO molecule. Thus, until the various reaction rates are better known, the ion spectrometer observation does not permit a choice between the Lyman alpha and the x-ray hypotheses.

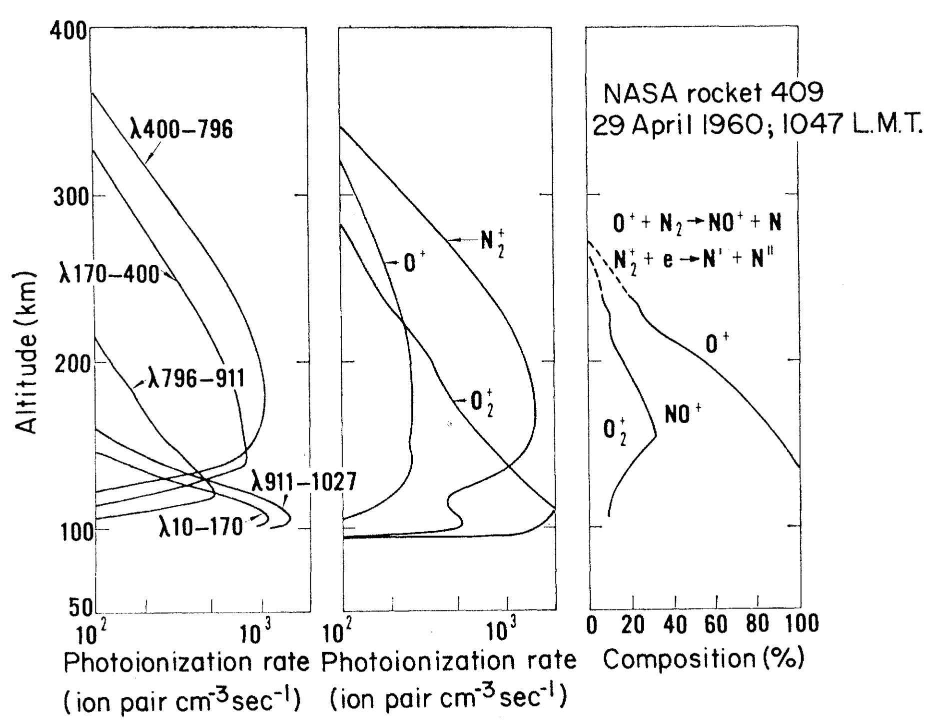

Fig. 5. Comparison of rate of production of ions (left and middle) with rocket measurement of ionic composition (right). [From Watanabe and Hinteregger (*29*) and Taylor and Brinton (*30*)]

Special D-Region Events

There are many phenomena which can enhance the electron abundance in the D region by two orders of magnitude or more, with associated electromagnetic-wave attenuation strong enough to produce radio blackouts. Simultanously with the appearance of a solar flare, increased absorption may be observed in the D region on the sunlit side of the earth, lasting for periods as long as an hour. The causative mechanisms for these sudden ionospheric disturbances were not established until investigators accurately timed rocket launchings during the course of a flare and observed enhanced x-ray activity in regions as low as 30 kilometers (*23*). The dominant role of solar x-rays in the production of these disturbances has been demonstrated by correlating visible flares with satellite observations of enhanced x-ray fluxes and with increased absorption of radio waves (*20*). An order-of-magnitude increase in D-region ionization during a sudden ionospheric disturbance has been measured with ground-based techniques (*15*) (see Fig. 3, curve *B*) and estimated theoretically (*19*).

At high latitudes, large increases in radio-wave absorption occur during auroras. These increases are attributable to enhanced ionization resulting from direct and indirect (bremsstrahlung) effects of precipitating energetic electrons (*22*). Evidence for an increase of as much as two orders of magnitude in electron density has been obtained (*18*) by launching rocket flights during such auroral events (Fig.

3, curve *C*). At the polar cap, above the auroral zone, another type of absorption occurs; it has been correlated with satellite measurements (*24*) of enhanced fluxes of energetic protons during certain types of solar flares. One rocket measurement (*25*) of enhanced electron densities during such polar-cap absorption events has been obtained (Fig. 3, curve *D*).

Increased radio-wave absorption not associated with solar flares is often observed in the winter in middle latitudes. The causes of these events are uncertain. It has been suggested, from ground-based observations (*15*), that these are associated with increases in electron density. However, the absorption may also be associated with changes in the frequency of electron collisions, A high correlation has been obtained between significant changes in ν and pressure variations measured in the stratosphere in two rocket flights during which the measured electron densities were approximately the same; this correlation suggests a meteorological influence on the D region (*17*).

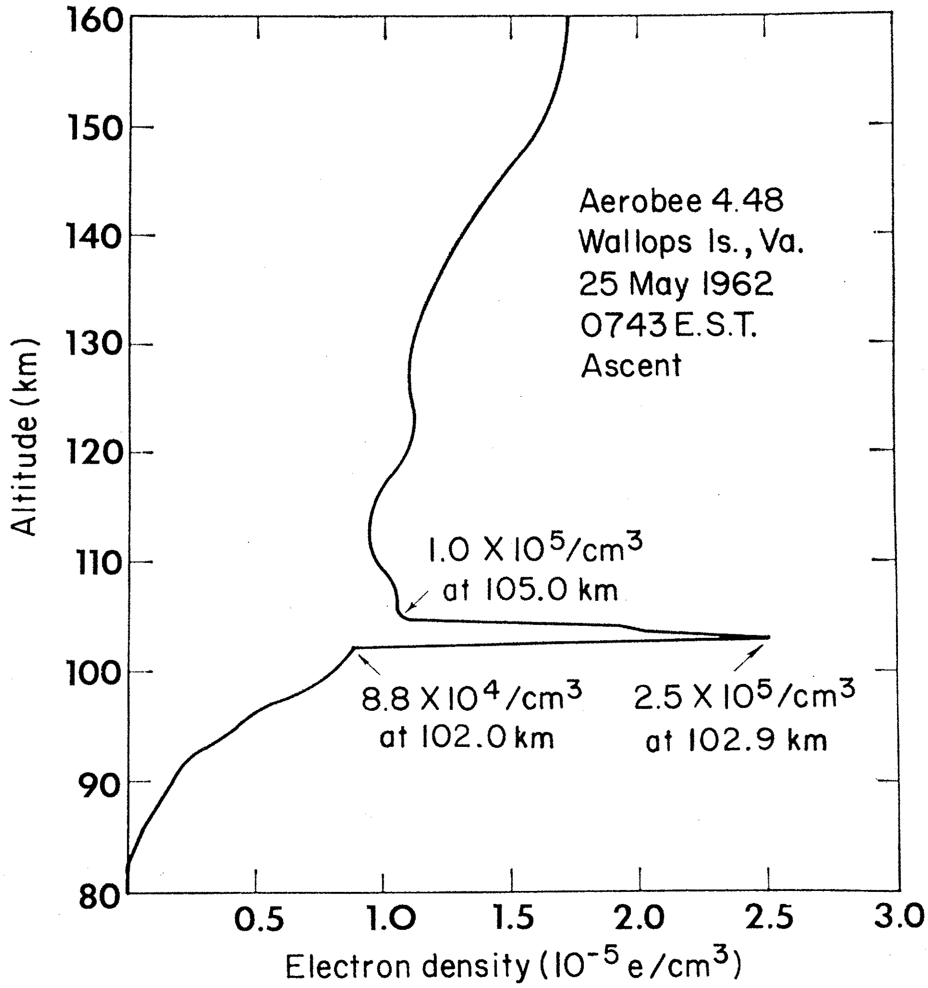

Fig. 6. Rocket detection of sporadic-E layer. [From Smith (*27*)]

The E Region

Although ground-based ionosondes have been valuable in providing details of variations, with time and latitude, in the maximum amount of ionization found in the E and F regions, the important variation of N_e with altitude has been determined by means of radio-wave propagation experiments (*26*) and plasma probe experiments (*27, 28*) aboard rockets. In Fig. 4, typical daytime and nighttime N_e profiles are plotted from such measurements. These show that at night the D region of ionization essentially disappears, electron abundance in the E region decreases 100-fold, and electron abundance in the upper F region persists strongly.

Other significant knowledge about the physics of the ionosphere has been provided by vertical cross sections of the intensity of solar radiation (*29*) and of ionic composition (*30, 31*). In important work (*29*), solar radiation measurements have been used, together with a model neutral atmosphere, in estimating the altitude dependence of (i) the rate of electron production for discrete portions of the x-ray and ultraviolet spectra (Fig. 5, left) and (ii) the rate of production for each of the ion species (Fig. 5, middle). We see that the ions with the highest rates of production are O_2^+, N_2^+, and O^+. On the other hand, spectrometer observations (*30*), typically represented in Fig. 5 (right), show that N_2^+ is a minor ionic constituent, despite the predicted high production rate. They also show that NO^+ is a dominant constituent of the E region, even though it is not produced in significant amounts by direct ionization. Most models (*32*) attribute the loss of N_2^+ to the combined effects of (i) dissociative recombination with electrons and (ii) ion-atom interchange ($N_2^+ + O \rightarrow NO^+ + N$). The existence of NO^+ generally is explained by ion-atom interchange involving N_2^+ and O^+.

It should be apparent that our understanding of the means by which the daytime E region is formed has been vastly increased by rocket measurements. Yet, models do disagree considerably as to even the relative importance of x-ray and ultraviolet radiation in the E region. Laboratory measurements of the various rate coefficients and additional rocket flights are needed to resolve these differences.

It is only quite recently that rocket experiments have been made sensitive enough for extensive studies of the nighttime E region. In Fig. 4 it may be seen that N_e drops below 10^3 cm^{-3}, and that the region is characterized by a peak at about 100 to 110 kilometers, with a valley just above. A comparison of the results from ion spectrometers flown both during the day and (for the first time) at night suggests that (*31*) that the maintenance of the nighttime E region is explained by a theory of slow decay through dissociative recombination, without resort to the assumption of a nighttime source of ionization. There also is experimental evidence, from rocket experiments, of metallic ions of meteoric origin in the 100- to 110-kilometer region.

A frequent anomaly of the E region is sporadic E ionization (E_s ionization). One common form of E_s ionization is a layer as thin as 0.5 kilometer in which N_e is considerably higher than it is in the regions immediately below and above; one effect of this layer is reflection of radio signals at abnormally high frequencies (Fig. 6). These layers exist at particular altitudes (*33*) in the 100- to 120-kilometer region. According to some theories (*34*), E_s ionization is the result of the combined effects of wind shear and electromagnetic forces. A correlation has been found between wind shear measured aboard one rocket carrying a sodium-vapor-release experiment and E_s ionization detected aboard a second rocket launched almost simultaneously (*27*). However, the exact relationship between E_s ionization and wind shear is not clear at this time.

The F Region

As shown in Fig. 4, the altitude of maximum electron density (N_m) lies within the F region. The region is subdivided into F1 and F2 regions, because a ledge often appears in the daytime 140- to 200-kilometer region.

It is important to note, in comparing Figs. 4 and 5 (left), that the altitude of maximum electron density lies well above the height of maximum electron production. These rocket results support previously established theoretical models in which the formation of the F2 peak is ascribed to charge-transport mechanisms comparable in importance to photochemical processes. Specifically, these models ascribe formation of the F2 peak to the competition between electron production, a height-dependent decrease in the rate of electron loss, and charge transport.

The rocket measurements of solar radiation and ion composition (see Fig. 5) show that F-region electrons originate principally through production of O^+ ions by solar ultraviolet radiation. The dominant process in the loss of electrons in the F region is believed to be radiative recombination, a two-step process involving (i) ion-atom interchange between O^+ ions and N_2 molecules, and (ii) recombination of the resulting NO^+ ions with electrons. The slowness of this two-step process partially explains the strong persistence of ionization in the nighttime F region. It is possible that the rate of electron loss decreases more rapidly with altitude than the rate of production; this would explain the experimental observations that N_m lies above the altitude of maximum production.

Because photochemical, gravitational, and electromagnetic forces all are effective, the behavior of the F region is extremely complicated. Ionosonde data obtained over the last three decades show that diurnal, seasonal, solar-cycle, and latitude effects all produce large variations in the magnitude and altitude of N_m (*32*). These observations have been related to data on time-dependent neutral atmospheres, deduced from measurements of satellite drag (Fig. 2), in estimating rates of ionization, loss, and diffusion (*35*).

As the density of the neutral constituents decreases, the importance of photochemical processes diminishes. Thus, charge-transport processes become dominant and bring about the observed decrease in N_e with altitude. Gravitational forces, for example, act upon the ions which, by coulomb attraction, cause the electrons to diffuse downward. In this case the hydrostatic law can be invoked, and the electron distribution is controlled by the average electron-ion temperature and the type of ion.

Before rockets and satellites had penetrated the upper ionosphere it was believed that the region populated by O^+ ions directly adjoined a higher region where hydrogen ions dominate. However, rocket (*9*) and satellite (*10*) experiments in 1960 indicated that a region of helium ions separates these regions in the daytime during the middle of the solar cycle. Other rocket results, obtained subsequently (*36*), suggest that the helium ion region disappears at night. It had been predicted (*11*), on the basis of the differing escape rates of hydrogen and helium, that both the altitude and the thickness of the helium ion region would diminish with decreasing temperature; such a diminution would imply a strong dependency on latitude and on stage of the solar cycle.

The roles of the temperatures of charged particles and of ionic composition in control of the ionosphere are illustrated by rocket measurements of charged-particle density at very high altitudes (see Fig. 7). Both a daytime (curve *B*) and a nighttime (curve *A*) result are illustrated. The exponential portions of both profiles provide evidence for a constant electron-ion temperature throughout the region, with values of 1300° and 800°K, respectively. In both cases the change of slope is interpreted as the result of a transition from O^+ to lighter ions, He^+ being dominant above this transition in the daytime, H^+ being dominant at night. It may be seen that the lower altitude of the transition and the relatively high abundance of H^+ produce the surprising result that at very high altitudes the nighttime densities exceed densities measured in the daytime. This may not be representative of a true diurnal variation because the two sets of data were obtained on different days.

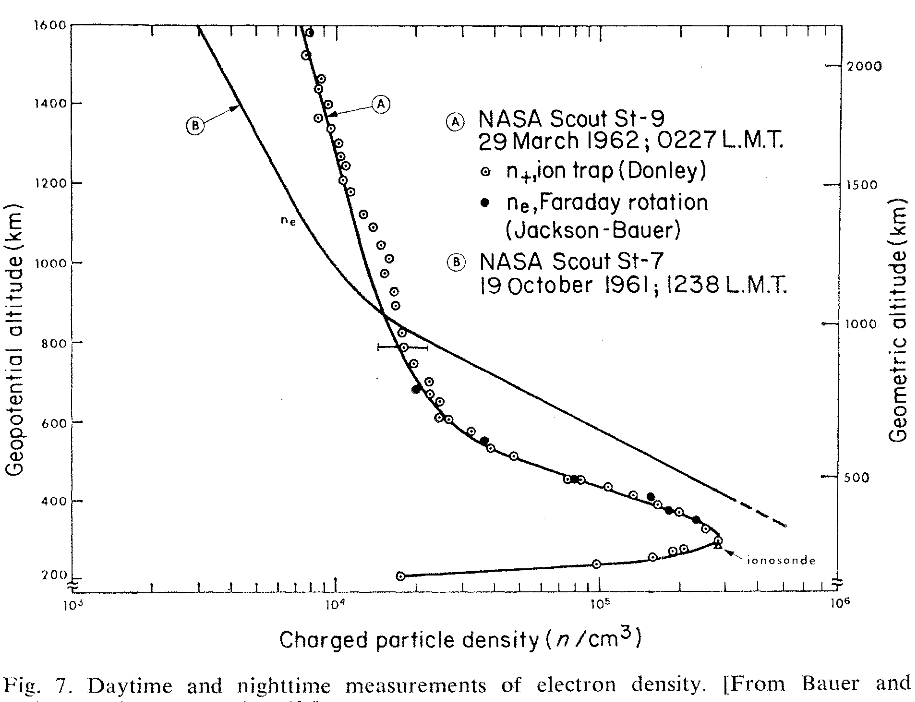

Fig. 7. Daytime and nighttime measurements of electron density. [From Bauer and Jackson (*50*) and Donley (*36*)]

Satellite Studies

Three different types of satellites have been used for ionospheric research, each performing a different task. With direct-measurement satellites, environmental sampling techniques

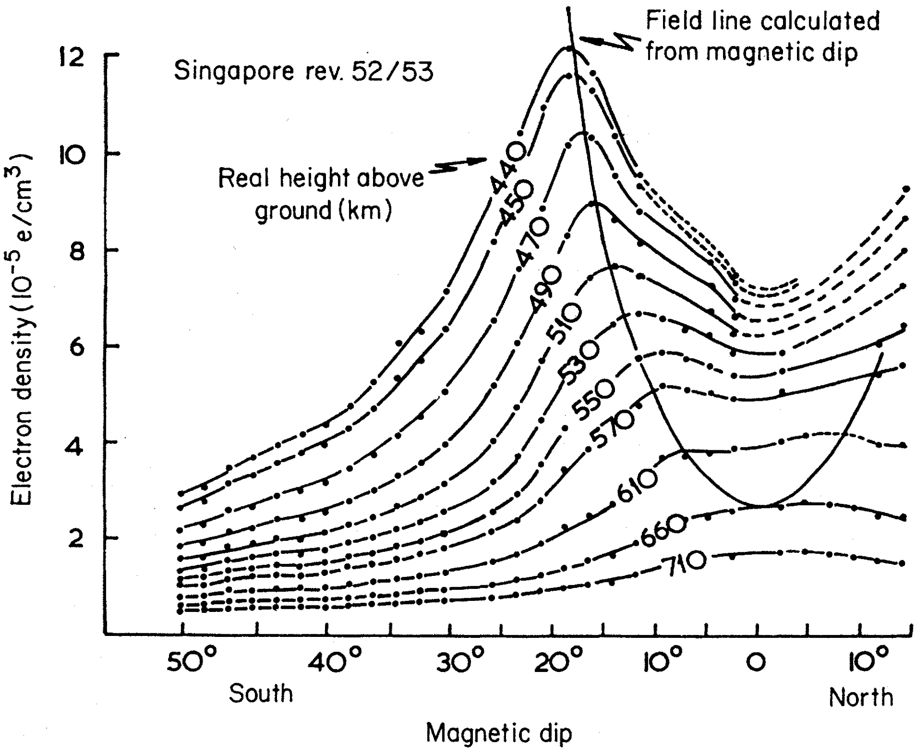

Fig. 8. Contours of electron density at constant altitudes measured above Singapore at 1000 hours, local mean time. [From King *et al.* (*37*)]

are used to measure many ionospheric parameters, but only in the immediate vicinity of the spacecraft. The U.S. satellite Explorer 8 and the British satellite Ariel 1 each carried three major experiments for such studies. The first of the three measures electron temperature by techniques similar to those developed by Langmuir in his laboratory studies of gaseous discharges. The second measures the local electron density by means of the radio-frequency impedance characteristic of a probe immersed in the medium. In the third, gridded ion traps are used, whose principle of operation is similar to that of an experiment flown on Sputnik 3. The high satellite-to-ion velocity permits the trap to act as a poor man's ion spectrometer; measurements for both ion composition and temperature are obtained (*10*).

In satellites of the second category (topside-sounding satellites) an orbiting ionosonde is used in an ingenious way. With this instrument, as with the classical ionosonde of ground-based ionospheric research, one measures the time between transmission of a radio signal and reception of the reflected echo. In the satellite measurement the reflection is from the top side of the ionosphere. By sweeping the frequency of transmission an electron density profile for the region between the F2 maximum and the altitude of the satellite is measured continuously along the satellite's path. Soundings of the upper ionospheric regions have been made in a near-polar orbit for over 2 years with the Canadian satellite Alouette 1, which carries a "swept-frequency" sounder. With a swept-frequency device one obtains good altitude resolution. The recently launched U.S. Explorer 20 carries instrumentation for fixed-frequency sounding, where vertical resolution is sacrificed in the interest of studying horizontal irregularities.

In satellite observation of the third type, workers at the earth's surface study the arrival characteristics of radio signals transmitted from the spacecraft at frequencies which penetrate the ionosphere. Faraday rotation and Doppler phenomena make it possible to measure the total content of electrons in a cross section between the satellite and the receiving site. The first satellite exclusively devoted to this method of observation is Explorer 22, launched too recently for results to be reported.

Satellite Results

The major results that have come from satellite studies are unique observations of the effects of latitude and diurnal change on electron behavior in regions above the F2 peak and of electron-density irregularities aligned with the magnetic field.

Evidence for magnetic field control of ionospheric electron densities was first obtained with ground-based ionosondes, which subsequently have provided details of the characteristics of the bottom side of the now familiar equatorial anomaly. The morphology of this anomaly has now been obtained, to altitudes of about 1000 kilometers. In Fig. 8 are presented results (*37*) from the Alouette satellite, showing electron density as a function of magnetic dip for discrete altitudes. These

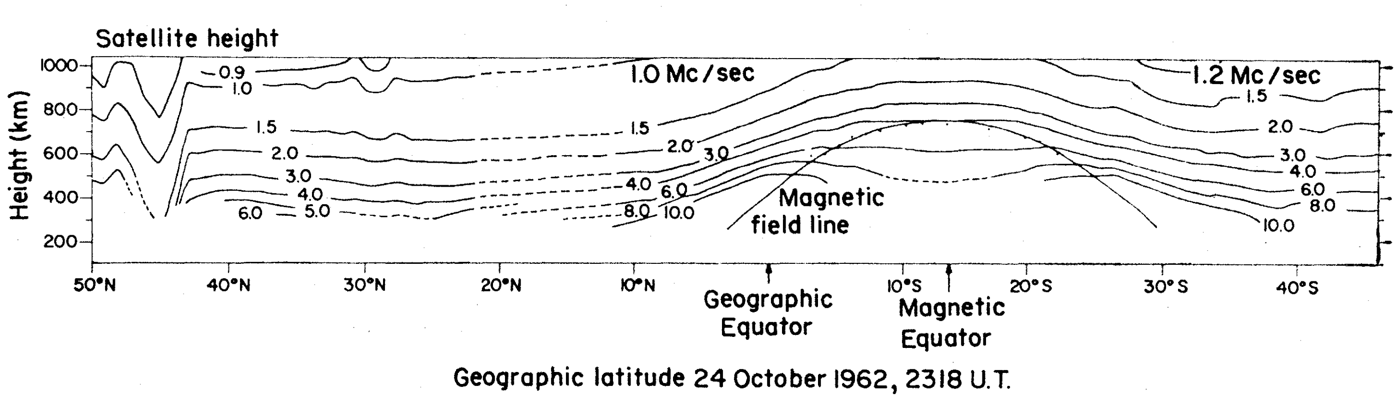

Fig. 9. Contours of constant frequency of radio-wave reflection measured aboard the Alouette satellite. [From Lockwood and Nelms (*38*)]

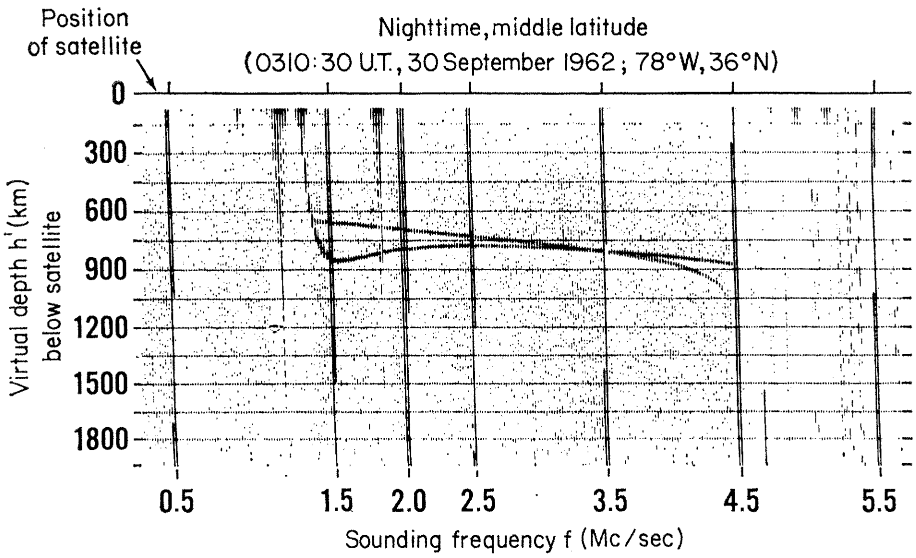

Fig. 10. Typical Alouette satellite ionogram recorded in the absence of the spread-F condition.

results are for the Eastern Hemisphere at 1000 hours local time. A general increase in electron density in the equatorial regions results from diffusion along the nearly horizontal lines of magnetic field. For the particular time of day represented, the electron density reaches a maxmum at the geomagnetic equator for altitudes above about 600 kilometers. Below this altitude two peaks are symmetrically located along a specific field line. The equatorial anomaly is predominantly a daytime feature of the ionosphere. The altitude above which only a single peak is formed has been termed the "dome" of the anomaly. The altitude of the dome over Singapore varies from 600 kilometers in the early morning and evening hours to a mid-afternoon maximum of about 1000 kilometers (*37*). Similar measurements (*38*) suggests that the anomaly builds up later in the day along the 75th west meridan. The diurnal behavior of the equatorial anomaly suggests that its characteristics are closely related to the competition between electron production, which tends to maximize N_e at the subsolar point, and diffusion along magnetic field lines, which tends to produce a symmetrical N_e distribution about the geomagnetic equator.

Another latitude-dependent feature of the top side of the ionosphere is the electron density trough, which appears to be a common phenomenon at middle latitudes during ionospheric storms associated with magnetic disturbances. Such a trough is illustrated in Fig. 9, a plot (for 65°W) of Alouette satellite measurements (*38*) of the frequency of reflections contours. The trough illustrated in Fig. 9 is less than 5° wide and is centered at 45°N.

Evidence for strong magnetic control of the upper ionosphere was first inferred from electron densities measured with a radio-frequency probe on the Ariel satellite (*39*). From these observations was inferred the existence of enhanced ionization along three specific magnetic-field shells, one of which is accounted for by the equatorial anomaly described above. The existence of these shells of enhanced ionization was confirmed, and others were discovered, by the Alouette satellite (*37*). Some of these shells have been associated with (i) the belt of artificial radiation produced by U.S. nuclear testing, (ii) the heart of the inner radiation belt, and (iii) ionization near the region of maximum flux of energetic particles in the outer radiation belt. All these observations suggest that high-speed particles should now be considered, along with ultraviolet radiation, an ionization source for the F2 region.

A very common anomaly of the F region is the "spread-F" condition. In which the region shows a diffuseness generally attributed to patches of ionization differing in density from that of the immediate surroundings. An ionogram (from the Alouette satellite) typical of a homogeneous ionosphere is shown in Fig. 10, the two traces corresponding to the ordinary and the extraordinary modes of radio propagation. The effectiveness of the spread-F condition in producing multiple echoes is illustrated by a comparison of this ionogram with that of Fig. 11, which was recorded during spread-F conditions. The probability of occurrence of the spread-F condition has been the subject of a thorough analysis with the Alouette satellite. This analysis (*40*) confirms the results of earlier studies with the ground-based ionosonde, which showed that the phenomenon is almost a permanent feature of

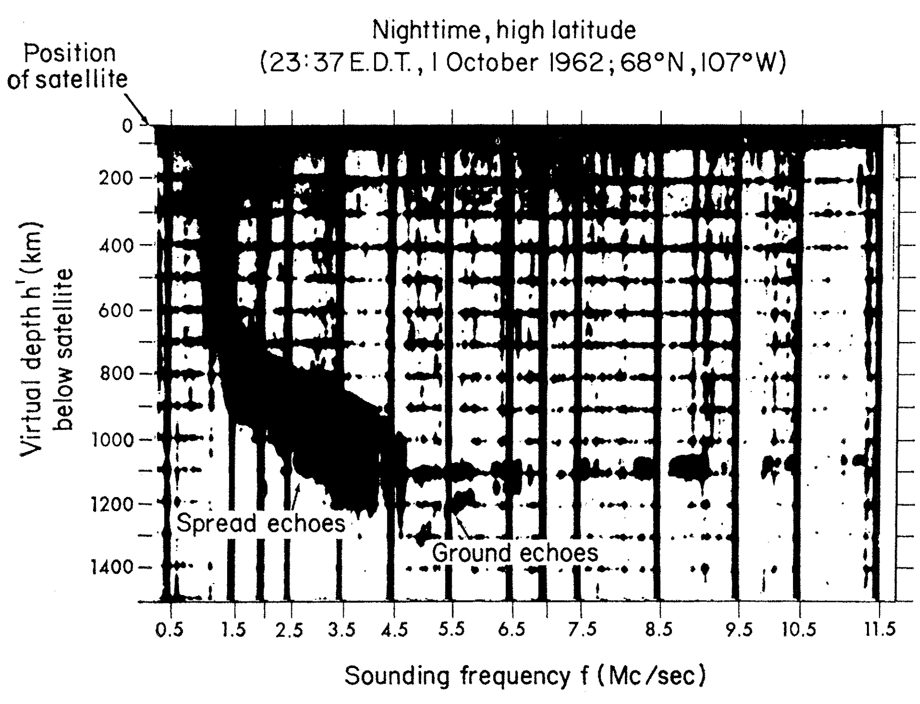

Fig. 11. Alouette satellite ionogram recorded during the spread-F condition.

the high-latitude ionosphere, that near the equator it occurs only during the night, and that it is relatively rare at mid-latitudes.

In Fig. 9 it may be seen that the electron density is not a strong function of magnetic latitude between about 15° and 45° north geographic latitude. We can expect to find that gravity plays an important role in the charge-transport mechanism in this region; if this is the case, the electron distribution is a strong function of the mean ionic mass and the average electron-ion temperature. The diurnal variation of the electron distribution in this region has been studied (*41*) by means of the Alouette satellite (Fig. 12). These studies have shown that the amplitude of the diurnal variation decreases with increasing altitude. This finding confirms a conclusion, based on the rocket results shown in Fig. 7, that, because of the increased relative abundances of the light ionic constituents, the electron densities above 1000 kilometers are higher at night than in the daytime. The diurnal variation shown in Fig. 12 has been studied in terms of ionic composition and temperature of charged particles. One possible conclusion is that, in the daytime, at 500 kilometers the principal ion is O^+, with an average electron-ion temperature of about 1500°K, while at night the lighter ionic constituents become more abundant even at altitudes as low as 500 kilometers (*41*).

Temperatures of Charged Principles in the Upper Ionosphere

Because electron temperatures (T_e) and ion temperatures (T_i) play a significant role in the behavior of the ionosphere above 300 kilometers, experimental observation of these parameters is important. Photoelectrons, at the time of their creation, possess energies greater than those of the ambient electrons. Some of this excess energy tends to be transferred to the ambient electrons, either through direct elastic collisions or, after some of the excess energy has been lost, through preliminary inelastic collisions with the ambient neutral particles or positive ions. As a result, the ambient electron gas is likely to be hotter than the neutral gas, at least in the daytime. It is a generally accepted hypothesis that at the lower altitiudes, where the neutral-gas density is relatively high, the ion temperature and the neutral-gas temperature are identical. It is possible that, at higher altitudes, where ionization is greater, the ions are in better thermal contact with electrons than with the neutral particles, and that consequently the ion temperature is higher than the neutral-gas temperature (*42*).

Measurements made with the Explorer 8 satellite were the first to indicate a strong diurnal control of ionospheric electron temperatures (*43*). Later results with the Ariel satellite (*44*) and with ground-based radar for determining incoherent backscatter (*45*) confirmed this diurnal dependency. The Ariel results and a comparison of radar observations of backscatter at two locations (*45, 46*) showed that T_e also depends strongly on magnetic latitude. Both the diurnal and the latitudinal dependency of T_e were subsequently confirmed (*6*) by means of the Explorer 17 satellite. The observations, considered together, show that in the daytime the electron temperature can be twice the neutral-gas temperature at certain latitudes and at certain hours.

Since some of the energy of newly created electrons is transferred to the ambient electrons, it follows that N_e and T_e should be strongly coupled. The changes in the behavior of T_e with latitude for the daytime ionosphere thus can be explained in terms of magnetic-field control of the electron density, at least at moderate altitudes. But it has been observed that T_e increases

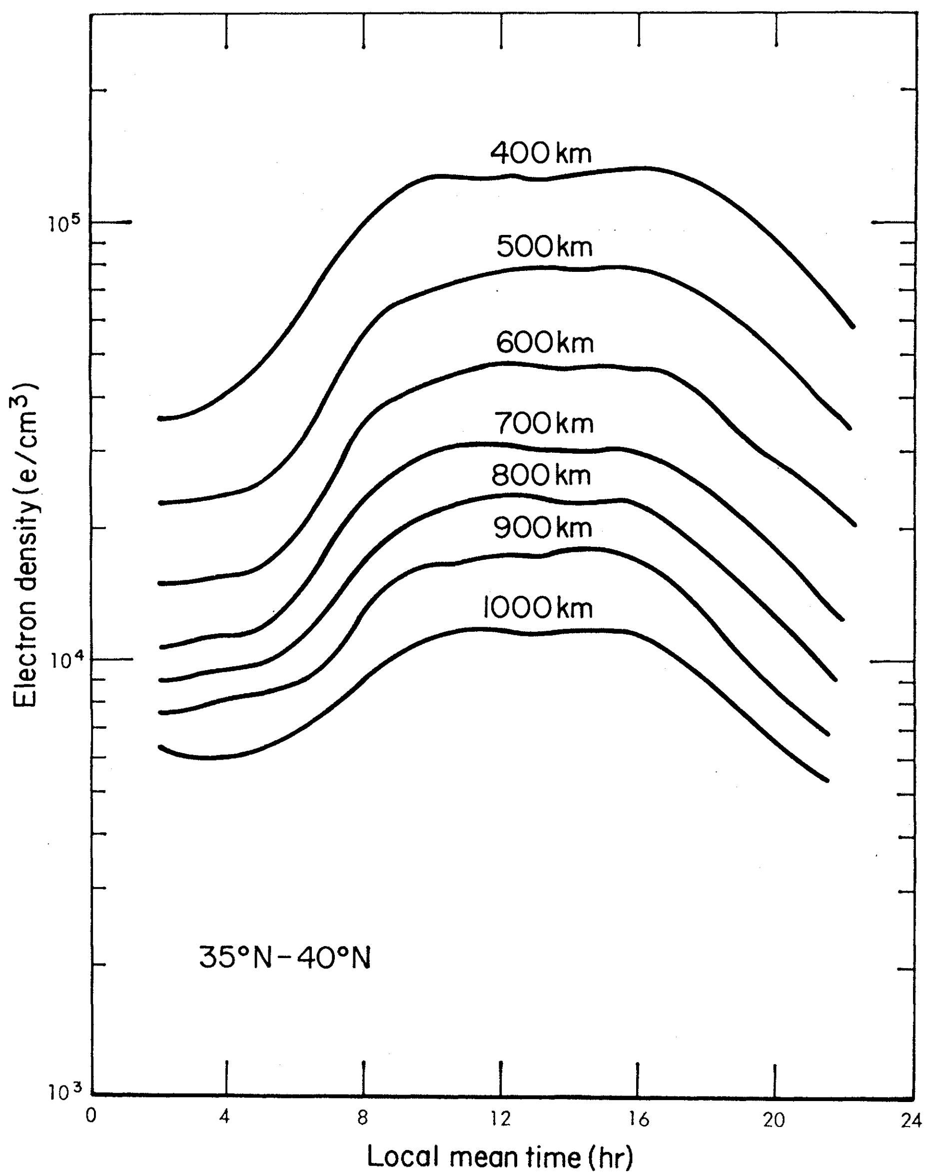

Fig. 12. Diurnal variation of electron density in the top region of the ionosphere. [From Bauer and Blumle (*41*)]

with altitudes above 600 kilometers (*44*). This would not be expected if direct ultraviolet radiation from the sun were the only source of heat of the daytime charged particle. The observations (*44*) are consistent with the hypothesis (*42*) of possible indirect effects of ultraviolet radiation—specifically, of a mechanism such that not all of the newly created electrons deposit their energy in the lower F region, where they are created, the energy of some being diffused along magnetic field lines and deposited at high altitudes. Another important observation (*6, 44*) is that the electron temperature is somewhat higher than the neutral-gas temperature at night. This finding implies a nighttime heat source having an intensity which is a small fraction (*44*) of the intensity of the daytime ultraviolet source.

The Upper Ionosphere

I have considered the higher altitudes to be subdivided into the F region, where O^+ ions dominate, and the upper ionosphere, where light ionic constituents are more abundant. Most observations show that, on the average, the altitude of transition between these two regions is about 600 kilometers. Satellite results from Explorer 8 (*47*) and Ariel (*48*) show that the transition is from O^+ to He^+ and then to H^+ as the altitude increases, at least during the middle of the solar cycle. These results also show that the thickness and altitude of the helium ion region decrease drastically from day to night. Other results show a more complicated behavior, in which, for nighttime conditions, and for all daytime conditions during the year of minimum solar activity, helium ions are never dominant. The exact morphology of the composition of the upper ionosphere is not yet clear.

It has been suggested (*49*) that the mean ionic mass is a function of the ion temperature. There already exists evidence (*45*) that the ion temperature in the upper ionosphere is controlled by the electron temperature, which, as I have shown, changes with latitude and time of day. It is becoming clear that theoretical models of the F region and the upper ionosphere, and of the interdependence of these two regions, need to be updated to include (i) gravitational forces, considered in combination with charged-particle temperatures and ionic composition, which vary with time and latitude; (ii) the possible existence of an ionization source, related to high-speed particles, which is superimposed on the ultraviolet source and which contributes to the maintenance of the nighttime ionosphere; and (iii) the possibility of indirect ionization from ultraviolet radiation—specifically, the effect of photoelectrons diffusing from the lower F region along magnetic field lines to deposit their energy at the higher altitudes. Thus, although satellite and ground-based studies in recent years have provided a preliminary description of the charged particle parameters at high altitudes, the observations need to be extended and correlated with measurements of photoelectron and high-speed particle fluxes before adequate theories of formation of these regions can be formulated.

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