Journal of Research of the National Bureau of Standards—D. Radio Propagation
Vol. 63D, No. 2, September–October 1959

Stratification in the Lower Ionosphere[1]

C. Ellyett[2] and J. M. Watts

(April 16, 1959)

A survey of the evidence for stratification in the ionosphere below 100 km is given, covering radio and optical observations, and rocket measurements. The conclusion is reached that one stratum at about 85 km is observed consistently, and that other fine structure exists but has no long-time constancy of height or pattern. There is no series of preferred heights below 100 km. The authors consider explanations which may account for the observations, and advocate the testing of radio methods of exploration in conjunction with rocket measurements in order to develop the most practicable means of obtaining accurate electron density versus height profiles on a synoptic basis.

1. Introduction

Gradually, over the past two decades, experimental results have either indicated directly, or have required the postulation of the existence of one or more discrete horizontal layers of ionization below the *E*-region of the ionosphere. Some of the most direct experimental evidence for such stratification has been obtained from vertical pulsed sounding of the ionosphere by Dieminger (1952), Gardner and Pawsey (1953), Gregory (1956), and others. However, many other unrelated types of experiment in the literature tend to support the concept of stratification, and, because of the diversity of experiments and the types of phenomena observed, the term "stratification" has been broadened in this paper to include, in addition to layers of ionization, any phenomenon tending to localize or show maxima at one or more heights, provided the effect is not purely transient in character.

The purpose of this paper is threefold: First, to search the literature for all references to discrete heights of phenomena occurring in the *E*-region and below; secondly, to present and compare models based on two different premises; and, finally, to discuss the avenues most likely to lead to further progress in exploring this region of the atmosphere between 50 and 110 km.

The references to discrete heights have been surveyed and grouped under the headings of radio, rocket, meteor, and optical phenomena, and are followed by a briefer study of the heights of occurrence of some of the relevant photoemissive processes. The existence of winds and turbulent air conditions in the lower ionosphere is well established and heights of these phenomena have in some cases been deduced. Sufficient material has been included to show the nature of the phenomena, but a comprehensive discussion of turbulence has not been attempted.

2. Radio Methods

2.1. Conventional Soundings

At first, workers were busy discovering the important characteristics of the *E*- and *F*-regions above 100 km, and paid scant attention to less prominent details. Appleton (1930), using a frequency change method of investigating the standing wave pattern of sky and ground waves, noticed "subsidiary fringes" which could be interpreted as the effect of extra layers in the *E*-region. Ratcliffe and White (1933) showed that some dual echoes which occurred in the *E*-region but never in the *F*-region were not magnetoionic components and were presumably from extra stratification. Both of these cases were probably from heights just above 100 km, and would now be called sporadic *E*, but Appleton and Piddington (1938) produced a histogram of echo heights showing a broad peak at 110 km, but significant occurrences of heights down to 80 km. In their opinion all echoes below the *E*-layer were transient in character and never of high strength. Appleton, Naismith, and Ingram (1939) discussed the application and limitations of the critical frequency method of determining maximum electron densities of the layers, and in so doing, mentioned the effects of thin layers, scattering centers imbedded in layers, thin sheets formed by coagulation of clouds of electrons, 90- to 100-km echoes (called trailing echoes), and *F*-region scatter. They also showed that sporadic-*E* reflections are from a preferred height. Ellyett (1947) collected early *D*-region information, and presented it together with some Pacific Island data from Pitcairn and Raoul Islands, showing that *D*-echoes were observed only during the day. Whale (1951), in summarizing the qualitative interpretation of regular ionograms, discussed subsidiary layers and evidence of irregularities in the *E*-region.

---

[1] This work was carried out in part under Contract AF 64(500)–3 from the U.S. Air Force Cambridge Research Center.

[2] University of Canterbury, Christchurch, New Zealand.

2.2. Experiments With Pulses at LF and MF

Pulse transmissions at low and medium frequencies have produced a large quantity of data concerning the lower ionosphere. Helliwell (1949) and Helliwell, Mallinkrodt, and Kruse (1951) observed at 100 and 325 kc, reporting heights from 86 to 106 km which were constant over periods of several hours, but which varied widely from day to day. At night "multiplicity of strata between 90 and 130 km" was observed. The separation of the echoes did not increase with order, which they interpreted, in the manner of Ratcliffe and White (1933), to mean stratification of the medium instead of echoes magnetoionically split. Helliwell (1952) also has shown that when histograms of observed reflection heights are plotted, certain "preferred heights" are evident. During August 1951 the values obtained were 100, 106, and 112 km.

Further information on observed heights of reflection may be found in Lindquist (1953) and Watts and Brown (1954). Lindquist reported vertical incidence results at 150 kc in the form of monthly median values of reflection heights. They were generally 85 km by day and 95 km by night. Watts and Brown produced low frequency ionograms with sweep frequency equipment, and reported heights in the forms of histograms and median values for 4 winter months. Day levels were from 70 to over 100 km, and at night the lowest level was 90 km. Several discrete levels were observed day and night, but in addition there was some evidence of turbulence in the lower reflections.

Kilpatrick (1957) has correlated low frequency ionograms with standard high frequency ionograms made near the same location. The results clearly indicate that some of the low frequency reflections have little or no relation to the normal daytime *E*-layer. In order to investigate the reliability of navigational systems—especially loran—Naismith and Bramley (1951) conducted a series of experiments using pulses from regular loran stations, modified broadcast transmitters on 668 and 877 kc, and regular vertical incidence sounders. Equivalent heights of reflection were computed for different ranges and days. They found a marked failure of Martyn's theorem concerning reflection delays at vertical and oblique incidence, indicating that partial reflections were important at oblique incidence. The lowest heights derived were 50 km at long range (1,208 km) to 85 km at 170 km. Two peaks, one at 75 km and another at 95 km were commonly present at intermediate ranges. At a range of 1,208 km the only prominent peak in the histogram was at 70 km.

In another oblique incidence experiment at 300 kc (Watts 1952 a), derived reflection heights were 70 km by day and 80 km by night. It is significant that the oblique incidence results gave lower heights than had been observed at vertical incidence at any frequency. Also when 2- and 3-hop modes were used to derive reflection heights, greater values always resulted, showing that the angle of incidence controlled the effective height of reflection.

Polarization tests of returned echoes have been made in order to resolve the question of the meaning of the apparent stratification in the region below 100 km. Benner, Grace, and Kelso (1950) used a crossed-loop polarimeter receiver to determine whether the split echoes were due to magnetoionic splitting, layer stratification, or partial reflection. They found the measured polarization precluded magnetoionic splitting, but it did not fit their theoretical limiting polarization. Watts (1952 b) used a circularly polarized transmitting antenna, with periodic switching of the sense of rotation. Most occasions showed that split echoes had appreciably different polarizations, as evidenced by different amplitudes when the sense was reversed, but in only one case were the split echoes of completely opposite sense.

In the low level region, disturbances by magnetic storms have the effect of making the region more transparent at night to the low and medium frequencies. Also, the fading is more rapid (Watt and Brown, 1951, and Lindquist, 1953). Lindquist also noted that SID's reduced the amplitude of the 150-kc reflections, but did not change their virtual height. This probably means that fadeouts are caused by an increase of ionization well below the reflection heights being observed.

Fejer (1955) used a pulse technique of novel type in an experiment involving interaction of two pulses in the ionosphere. By adjusting the timing of the two trains of pulses, the height at which they coincided could be altered. The method enables a determination of both electron density and collision frequency versus height to be made. He derived a profile of electron density showing ledges near 72 and 78 km, presumably in the daytime. The method seems potentially powerful but, like most interaction techniques, requires dealing with very small effects.

2.3. Experiments Involving VLF Using Either CW or Sferics

An approach to lower ionospheric understanding by means of long wave propagation has interested some other workers. It was hoped that the experiments would prove that a simple model would suffice to predict propagation characteristics.

Weekes (1950) at 16 kc found that the reflecting layer changed its characteristics between 300 and 500 km distance from the transmitter. At less than 500 km the received polarization was circular and the reflection height was either 67 or 75 km, depending on alternative phase changes assumed upon reflection. At 500 km or greater the polarization was linear, but the height was not determined. Bain and Bracewell (1952) proposed that two different reflective heights, having different diurnal characteristics, would explain the VLF phenomena. Bracewell (1952) postulated a new theory of layer formation to explain the downward extension of ionization observed during an SID, and also that there must be a separate layer below the *E*-layer. Bain (1953) went further, requiring two layers below the *E*, and requiring that the SID effect was a downward extension of the top layer without change in the nature of its ionizing reaction. Hopkins and Reynolds (1954) still later considered the problem, and decided that difficulties of interpretation arise when more than one wave of appreciable magnitude is received and that their results gave only a broad description of oblique LF and VLF propagation.

Rivault (1950) observed that the average height of reflection of sferics in October, 1949, from 1700 to 2100 hr was 75 km, and mentioned marked changes in the height of reflection during a magnetic storm. Caton and Pierce (1952) observed that sferic waveforms arising from the southwest were different from those arriving from the southeast, which seemed to indicate that the earth's magnetic field influences the propagation. Their reflection heights averaged 86 km at night. Daytime waveforms were not suitable for analysis. Hepburn and Pierce (1953) deduced a daytime height of reflection of 65 km, and a nighttime height of 90 km, from observations of the "slow tail" of sferics.

In 1953 Budden attempted to fit the accumulated VLF observations of field strength versus distance into a model consisting of a sharply bounded, homogeneous ionosphere and a perfect earth as a waveguide, neglecting the earth's magnetic field. A computer was used to calculate waveguide modes and by trial to select parameters which fitted the observed field patterns. He found that the four least attenuated modes explained the measurements if a height of $69.1 \pm .05$ km was assumed, together with a collision frequency of 1 to 3×10^7/sec and an electron density of 135 to 400/cm^3 at the boundary. This was a daytime model.

In a later analysis, Wait (1957) showed that some of the modes (called negative order by Budden) had no physical significance. Using the corrected form of the mode expansion and a sharply bounded lower ionospheric model, Wait compared calculated field strength versus distance curves with the best available experimental data for daytime trans-Pacific paths. For frequencies in the range 16 to 25 kc the agreement was good for all distances if the collision frequency was taken as 10^7/sec and the electron density as 1,000/cm^3 at a reflection height of 70 km. At night the reflection height deduced was variable, but it seemed to be near 90 km. Also, some calculations by Wait and Perry (1957) of ionospheric reflection coefficients for a sharply bounded, homogeneous medium, with the magnetic field included, show a change of polarization and of phase of the $_{//}R_{//}$ coefficient with range indicating a quasi-Brewster angle effect which may explain the existence of the changeover in reflection characteristics observed by the earlier workers at intermediate ranges.

In summary, a complicated stratified region is probably not needed to explain the VLF results, but if the medium is so complicated, there may be subtle VLF effects as yet unobserved. As an example of such refinements, Wait (1958) has found it expedient to introduce a two-layered model in order to predict the field strength versus distance characteristics at frequencies lower than the range 16 to 25 kc considered in the earlier paper (Wait, 1957).

2.4. Theoretical Work Applying to Propagation of VLF and LF

A lack of analytical solutions of the equations of wave propagation in inhomogeneous anisotropic media for the general case applying to the lower ionosphere has plagued all experimenters. However, approaches have been made in two ways; first by finding approximate solutions of the wave equations, and secondly by devising digital computer techniques for integrating numerically the wave function through the medium. In both cases models of the lower inonosphere must be proposed, tried, and modified until the results fit the observed characteristics. With reference to stratification several workers have argued that split echoes do not necessarily imply stratification, since their theoretical work predicted a "coupling echo" in addition to the regular echo from a single layer. See Nertney (1952), Gibbons and Nertney (1952), Nertney (1953), Davids and Parkinson (1955), and Parkinson (1955). However, Budden (1955) in a complete treatment and some trial solutions by the numerical integration method, did not mention the extra echo. If the phenomenon exists, and his matrix $\overline{R}$ were plotted against height, it should exhibit the contribution from the extra "coupling" echo in appropriate levels. Poeverlein (1958) presents an analytic method consisting of approximation by very thin slabs which, according to the author, reduces to values equivalent to Budden's matrix $\overline{R}$. Both Budden and Poeverlein demonstrate a "quasi-Brewster angle" phenomenon with changing angle of incidence. (See comments referring to Wait and Perry (1957) above.) In summarizing this and the previous section, it should be noted that none of the methods discussed have enabled unambiguous, direct deductions of values of electron density and collision frequency versus height to be made. These should be the fundamental objectives of all ionospheric research.

2.5. Experiments With VHF Ionospheric Propagation

Research in VHF ionospheric propagation soon revealed that the signals were in general being returned from below the E-layer. Bailey, Bateman, and Kirby (1955) listed daytime heights between 75 and 80 km and nighttime heights of 85 to 90 km. The lowest height observed in some pulse tests was 59 km, and often several "strata" were simultaneously active. Pineo (1956) reported heights of 70 km by day and 86 at night, with frequent observation of two daytime reflection heights of 73 and 89 km simultaneously. It is quite apparent that these discrete heights at VHF cannot be explained by magneto-ionic splitting, and although there may be other difficulties of interpretation, these observations refute the idea that stratification is physically impossible in the region.

2.6. Lower Ionosphere Pulse Techniques at MF, HF, and VHF

Dieminger (1952 and 1954) called attention to the fact that low-level echoes were being observed in Germany by a conventional ionosonde. He observed the following characteristics:

(*a*) The echoes could be seen from 1.6 to 4.0 Mc at heights of 75 to 90 km in the daytime.
(*b*) There was a diurnal variation of height with a minimum at noon.
(*c*) The low levels merged with a 95 km level at night.
(*d*) The heights of all echoes were independent of frequency.
(*e*) There was a correlation of the absorption of higher level echoes with the height of the lower levels.
(*f*) Low level echoes were most frequent in winter, and occurred in groups of days.

In Dieminger's opinion the echoes were produced at a sharp boundary, but the echo structure was patchy, indicating an inhomogeneous medium. Meteor dust was proposed as the cause of a permanent nighttime echo at 95 km. He also concluded that the results were strongly influenced by meteorological phenomena, and that synoptic data over the world might be necessary to understand them. At about the same time, Gnanalingam and Weekes (1952) reported heights of 75 to 80 km on winter days of high absorption, but on other winter days heights of 90, 96, and 112 km were common. They used a sensitive frequency modulation technique to detect the weak signals. Later Gnanalingam and Weekes (1955) speculated on the nature of the region responsible for their observations. They argued that the echoes were not caused by gradients, because gradients would be destroyed by diffusion above 80 km, and gradients alone would not explain the absorption effects impressed on reflections from higher regions. They required a separate layer in the *D*-region which became totally reflecting at times at their frequencies (1.4 Mc). A histogram of all observed heights near noon during January and February 1952 and December 1953, showed no preferred values. The lowest height was 74 km.

Some lower ionospheric information has also resulted as a byproduct of auroral radar studies. Forsyth, Currie, and Vawter (1953) reported backscatter on 56 Mc which they deduced came from a level of 85 km. Similarly McKinley and Millman (1953) occasionally received vertically incident echoes on their 33-mc meteor radar at an approximate height of 80 km, night and day.

The first pulse experiment especially designed to study the lower ionosphere at vertical incidence at a fixed frequency above all critical frequencies of the region was described by Gardner and Pawsey (1953). They used a fixed frequency of 2.28 Mc and an overall sensitivity 30 to 40 db greater than Dieminger. Daytime echoes were regularly found at heights of 60 km and up. Field strengths of the different components differed by factors of up to 10^4, and no echoes were ever observed below 55 km. Echoing layers seemed to come and go at fixed heights. Their heights were classified in groups at 70 km, 90 km and normal *E*-layer levels. Histograms of heights were also shown, arranged by the hour, and by the day. The lowest height showed a pronounced diurnal variation. The echoes returned from levels below 76 km were composed of a larger component of extraordinary polarization than of ordinary, suggesting that these were, indeed, partial reflections from less-than-critical density clouds of electrons in the region. In pursuing the analysis of the phenomenon Gardner and Pawsey show the theoretical basis for, and use of, a method of deriving a complete profile of electron density versus height in the region. Derived profiles are given for noon on two days in May. One shows maxima at 64 and 73 km. The other has maxima at 68 and 73 km. The authors conclude that most absorption of HF waves is above the 70-km region and that this region, although at a definite level having separate existence, is under some kind of solar control. They think that VLF propagation characteristics can be explained, using their results.

It should be mentioned that Appleton and Piggott (1954), being interested in the absorption of HF waves, investigated Dieminger's observations of low level echoes in winter by studying other regular ionograms. Again they found that occurrence of winter days of high absorption is directly correlated with the occurrence of sporadic reflecting strata below the level of the *E*-layer.

Gregory has used a vertical pulse equipment at 1.75 Mc of considerably greater sensitivity than that of Gardner and Pawsey, together with an antenna of 12 db gain directed vertically. His first paper (1956) gives results which not only confirm the stratification observed by Gardner and Pawsey, and Dieminger, but also show much additional detail as a result of the greater sensitivity. This enabled him to deduce or substantiate the following:

(*a*) The existence of a modification of the *E*-region at 95 km, capable at times of total reflection, and showing some measure of solar control.
(*b*) The continuous existence, night and day, of a second region, having a lower boundary near 85 km.
(*c*) The existence of a complex series of partial reflections, during daytime only, extending down to 53 km, with a marked increase in strength and rate of occurrence at the lowest heights during winter months.
(*d*) The complete absence of reflections from heights below approximately 50 km.
(*e*) A relation, on winter days of high absorption only, between *E*-region echo strength and partial reflections from the heights 66 to 85 km.
(*f*) The findings of Dieminger that the low level echoes had a tendency to occur in groups of consecutive days, perhaps accounting for the winter absorption anomaly.

Observations of discrete heights at 95, 85, 75, 67, and 53 km seem common in Gregory's work.

Gregory (1957) published a comparison of heights observed at 1.75 mc with those reported by Pineo (1956) at VHF oblique incidence, pointing out the remarkable similarities between the two with respect to heights and diurnal variations. The suggestion was made that the two approaches (MF and VHF) should be regarded as complementary ways of investigating the nature of the region. A new low height commonly occurring on winter nights was found by Gregory (1958a) to be near 75 km, as contrasted with the 85-km limit observed by the earlier workers.

Gregory (1959) states that equipment for recording *D*-region echoes has recently been installed at Scott Base, 78°S, in Antarctica, and that reflection heights similar to those in temperate latitudes are being recorded. Initial results show that the all-daytime summer heights lie between 62 and 90 km, with the 90-km height present continuously. The fading rates are faster than at temperate latitudes.

Landmark (1958), in observations at 2.3 Mc of three polar blackouts, found that 65- to 70-km echoes appeared, but only when the main echo was increasing in amplitude (recovery period). The statistical significance of three cases may be somewhat doubtful, but polar blackouts are another phenomenon of great interest to which too little attention has been paid.

Bowles (1958 and private communication) has accomplished what amounts to a *tour de force* in the field of vertical incidence observations using pulses. With a transmitter capable of 4 to 6 megawatts peak pulse power, together with a 1024 element directive antenna, he has succeeded in obtaining reflections at 41 Mc which extend from the lower ionosphere continuously through to above the *F*-layer during the daytime. In particular, echoes, attributed to turbulence, are observed continuously at 60 to 90 km height. At any time several different strata are observed, but their continuity in time has not been established.

3. Rocket Observations of Electron Density—Height Profiles

The use of rockets over the past six years has introduced a powerful new tool in the study of the lower ionosphere. Much which in the past had to be inferred by remote radio and optical probing can now be measured directly. In this section only those rocket flights giving information on the electron density-height distribution are discussed. Other flights designed to give information on wind movements or on photoemissive processes are included in following sections on these subjects.

While rocket flights can give results on electron concentrations in the lower ionosphere, they must be treated with caution, because: (*a*) Experimental techniques are complex, and in some cases have known possibilities of error; (*b*) instrumentation has been adjusted for electron concentrations of the order found in the *E*-region. Consequently strata appreciably below *E*, of roughly 100-fold lower concentration, have hardly been recorded at all; and (*c*) the total observing time for all rocket flights is still extremely small, and hence a knowledge of the basic structure could still to some extent be obscured by local abnormalities.

Nevertheless, sufficient results are now available to show a fairly consistent pattern above about 88 km, with small concentration peaks and ledges superimposed on a steadily rising electron concentration with height. The rocket usually traverses a different part of the ionosphere on the upward and the downward portions of the flight, and either this space separation effect, or a fading or turbulent effect arising in the few seconds between the two portions of the flight, is sufficient in some cases to remove, or to alter the height of minor concentration peaks.

In 1953 Lien and coworkers reported four profiles, which differ in appearance, but three show a concentration peak at about 97 km, and two show peaks at 111 and 122 km. Observations were continued by Seddon, Pickar, and Jackson (1954), with peaks appearing at 101, 113, and 128 km. During the descent the 101 peak did not reappear. Jackson and Seddon, working with good equipment in 1958, find a strong peak at 101 km due to a sporadic-*E* layer, not more than 1 km thick. Again Pfister and Ulwick (1958) show peaks for one flight at 106, 111, 117, and 128 km, and comment on intense irregularities.

Jackson, in 1954, obtained daytime free electrons as low as 73 km. This was supported by Seddon, in 1958, who obtained a measurable electron density at 74 km, and also observed an abrupt ledge at 86.5 km.

4. Influence of Winds and Turbulence

4.1. Experimental Evidence

(*a*) *Radio echoes.* The ionosphere exhibits the characteristics of movement at all levels. As an example, sporadic-*E* clouds can be traced as they move bodily from one geographical location to another. The paper by Thomas and Burke (1956) gives an account of some of the deduced characteristics of these clouds. Their heights are above 100 km, their thickness is probably not greater than 1 km, and the horizontal extent is of the order of 10 km. It may be that similar structures can occur in the lower ionosphere.

Experimental work in studying motion of the lower ionosphere has invariably produced evidence that the apparent velocities change with height, sometimes very abruptly. Briggs (1951) found irregularities to be localized in height, using a frequency sweep technique which produced an interference pattern independent of ionospheric motion. By using a low frequency (150 kc) and supplementing the usual amplitude pattern with a phase height measurement, Jones, Millman, and Nertney (1953) reported that their fading was produced at heights of 74 to 77 km by day, and 83 to 100 km at night. Another report of 150-kc observations was by Banerji (1955), who found day heights for irregularities to be lower than at night (78 versus 87 km). Bowhill (1956) studied fading phenomena observed from 16 to 2,400 kc, and suggested that a model containing small irregularities above the 70-km level and large ones below this level might explain the fact that a mixture of two different types of fading was observed. Later, Bowhill (1957) in a study of nighttime reflection levels of 75- and 150-kc pulses, came to a similar conclusion, but decided that the more rapid fading was due to irregularities above 100 km. Parkinson (1956), dealing especially with the nighttime 90-km echo, also found that it had two different characteristic fading frequencies, preseumably impressed upon the wave at two different levels. I. L. Jones (1958) reports that on two nearby frequencies, 2.0 and 2.5 Mc, the wind velocities were significantly different, perhaps because the fading was imposed by scattering near their different reflection levels. Also, the directions of the winds observed at the two frequencies rotated diurnally, the rotation at the greater height (higher observing frequency) leading that of the lower height. The phase lead amounted to 7 or 8 degrees per kilometer of height, thus showing wind shear.

(*b*) *The movement of meteor trails.* Again an appreciable body of literature has grown up in the past decade on meteor trail movements. Radar echoes from the trails of large meteors provide a powerful and direct method of observing movements in the 80- to 110-km region. Both steady movements, varying in direction with height and time, and turbulence are observed. Typical results are given by Greenhow (1952 and 1954) and Greenhow and Neufeld (1955 and 1956). They find that turbulent winds always occur between 80 and 100 km. There is a gradient of about 2.7 m/sec/km, but large irregularities in speed and direction are observed in a few minutes—occasionally amounting to complete reversals. Root mean square values of turbulence of about 30 m/sec are almost always observed. In their second paper they find that the height gradient of prevailing velocity was uniform at 0.5 m/sec/km ht.

A full statistical study of the accuracy of meteor wind measurements has been made by Manning, Peterson, and Villard (1954), who find strong evidence of layered horizontal winds in the 80- to 100-km region, with some superimposed irregular turbulent motion. Liller and Whipple (1954), photographing the movement of meteor trails, support these results by finding circulatory or turbulent winds moving in opposite horizontal directions separated by short vertical distances. Observed vertical wind shears averaging a greater maximum than 50 m/sec/km are not particularly concentrated at any height.

The literature contains many photographs and reports of long persistent meteor trails, showing in every case large amounts of relative movement. An excellent example is afforded by the artificial sodium trail created during a rocket flight (Edwards, Bedinger, and Manring, 1955). A photograph of the trail shows extensive shear distortion, and a complete reversal of wind direction was observed between the 85 and 110 km levels. These observations constitute convincing evidence that the motions are indeed true winds in the lower ionosphere. Other evidence is the motion of noctilucent clouds and airglow cells (Ludlam, 1957, and Roach, et al., 1958) discussed below.

4.2. Theoretical Aspects of Turbulence

The implications of the existence of turbulence and/or winds in the lower ionosphere have been studied because of the large influence they have on radio propagation. Herlofson (1951) pointed out that plasma resonances similar to those predicted for meteor trails could be expected for any small ionospheric irregularity. As a direct consequence, single-ray fading from this cause should be more important near the critical reflection level, and one should be able to identify a change of reflection level with a consequent change in fading characteristics by changing the probing frequency. As an extension, partial reflections from irregularities would be expected to show rapidly varying fading characteristics near the plasma resonances of the irregularities as the frequency is changed. (See the discussion of I. L. Jones (1958) above.) Polarization of the reflected wave could perhaps be examined to detect elongated field-alined irregularities.

In a paper by Maxwell (1954) turbulence in the *F*-region is primarily dealt with, but the author makes the statement that "the *E*-region will invariably be turbulent" with a microscale (small eddy size) of 10 m.

Gallet in two papers (1951 and 1955) develops a theory using the physical variables in a turbulent region to explain some of the radio reflective properties of the *E*-region, first as an explanation for the sporadic-*E* reflections, and then for some of the lower ionospheric phenomena. In a model region, vertical transport of eddies or "blobs" of air changes their pressure, density, and temperature. The contrast in electron density presented by a blob against the background of its new location is a function of two sets of circumstances. First, how different its electron density was before it was moved with respect to the surrounding electron density of the new location, and secondly, how different a volume appears to be to the exploring radio wave due only to the changes of pressure, density, and temperature with height. The first situation is obviously of maximum effect near a sharp electron density gradient or, in the case of a single layer, above and below the maximum. The second situation requires no gradient of the average electron density, and therefore requires no layer; and the position of maximum contrast would be entirely a function of the localizations, if any, of the turbulence characteristics. In application, these two mechanisms could give maxima at different levels, recalling the question of the interpretation of split echoes from the lower ionosphere.

The idea of turbulence due to ionospheric wind motions has become a very useful one in attempting explain many ionospheric phenomena that have been known, but seldom studied. Booker (1956) has listed many phenomena that he considers can be explained by turbulence in the ionosphere, including fading of single rays, the distortion of meteor trails, *D*-region echoes and VHF forward scatter. Booker conjectures that the latter two are caused by the same irregularities. (See Gregory (1957) and Bowles (1958).)

As an example of an interesting application of the gradient mixing type of turbulence theory (see Gallet above), Wheelon (1957) has tried a model of the lower ionosphere which might explain the VHF forward scatter observations, particularly the diurnal variations, as described by Bailey, et al. (1955) and Pineo (1956). The model starts with a very steep gradient of ionization at 70 km of 2,300 electrons/cm^3/km to provide the observed daytime field strength, and includes another rise between 75 and 88 km to account for the nighttime residual signal after the 70-km daytime component has decayed.

The existence of winds and turbulence in the lower ionosphere may provide a coupling link between that region and the next lower region. As an example of the type of meteorological work which may eventually establish a link between the two, the paper by Fleagle (1958) is of interest.

5. Survey of Meteor Height Results

Extensive studies of meteors entering the earth's atmosphere have been made by visual, photographic and radio echo methods, particularly in the last decade. This work gives information relevant to the present inquiry in the fields of meteor ionization height, and the influence of fine meteoric dust.

Many papers report studies of the height of occurrence of the light and the ionization from meteor trails. The mean height of maximum ionization of visual size meteors is close to 95 km (Hey and Stewart, 1947; Millman and McKinley, 1949). Analyses of both visual observations, given by Porter (1944), Prentice (1948). and others, for the beginning and end heights; and of radar echoes given by Evans (1954) and others for the height of maximum ionization, show that these are clear functions of meteor-velocity. The height of maximum ionization for the smallest detectable meteors falls from 105 to 85 km as the incident meteor velocity decreases from 60 to 20 km/sec.

The effect of initial meteor size on the height of maximum ionization is much less marked than the velocity effect. Prentice, recording visual results, finds that large meteors extend over a greater height range than small meteors, but Millman (1957), observing radar echoes in Canada, finds no mean variation in height between meteor magnitudes of -6 and $+4$. From this Millman concludes that the atmosphere is the controlling factor in determining the height of maximum ionization. This result agrees with the work of McKinley and Millman (1949) who, on the basis of a considerable body of radar echo observations, conclude that the 90- to 100-km region has fine structure, or localized regions which prolong the existence of meteoric ionization at specific heights. As a result of further analysis, Millman (1957) reports the possible occurrence of peaks of ionization at 92, 98, and 106 km.

Herlofson (1948), however, deduced theoretically that the atmospheric pressure at the point of maximum luminosity of a meteor is directly proportional to its pre-atmospheric radius. Since pressure is a simple function of height, this work implies that smaller meteors create their maximum ionization at a greater height. This conclusion is supported theoretically by Kaiser (1953), who places the maximum ionization effect of small meteors at heights between 130 and 115 km.

There is obviously a discrepancy between the smooth transition to greater heights with decreasing meteor size predicted theoretically, and the height independence of size, and the stratification, observed by the Canadian workers. However, it can at least be concluded that practically all significant meteoric ionization produced by large to near micrometeoric size particles, appears well above the mesopause height of 82 km, and well clear of the ionospheric stratification observed by Gregory at still lower heights.

Micrometeorites have been shown by Whipple (1952) to be so small that they are capable of deceleration to zero velocity by the drag of the earth's atmosphere, without ablation occurring. Ablation was necessary in Herlofson's model for the production of ionization. Consequently micrometeorites were disregarded as a source of ionization until Dubin (1955) produced evidence that highly velocity-sensitive ionization could be produced without ablation. The number of such particles is great, and on extrapolation from the Herlofson and Kaiser theories such ionization, if produced, should occur at still greater heights than that produced by the smallest ablating meteors. (Dubin has assumed, without justification, that the micrometeorite effect occurs at the height of sporadic *E*.)

On this basis Gregory has assumed, along with others before him, such as Deb (1940) and Paton (1951), that meteoric dust residues, and presumably also micrometeorites, would drift down to and concentrate at the temperature inversion level at about 82 km. There, the mechanism of photoionization of dust particles by solar radiation, suggested by Eckersley in 1948, might give rise to further ionization during the daylight hours.

The subject, however, is now further complicated by the recent analysis of Öpik (1958), who concludes that micrometeorites reach directly to, and have their maximum temperature in the region 70 to 90 km. If Dubin's suggestion—by analogy with shock-tube experiments—that such neutral particles can indeed produce appreciable ionization by velocity alone, is accepted, then a new source of low-level ionization is apparent. Further experimental work on the variation of the height of maximum meteor ionization with decreasing particle size is clearly required.

Evans (1955) in the northern hemisphere, and Weiss (1955) in the southern hemisphere, find no seasonal effect in the height of meteoric ionization.

6. Summary of Optical Results Giving Height Information

Observations of scattering of the sun's rays by the atmosphere at twilight give evidence of discontinuities in the lower ionosphere. Even at night the sky is not without light, but always has a faint glow. In the past 5 years the heights of emission of various spectral lines in the airglow have been determined with increasing certainty. On occasion noctilucent clouds are also visible at great heights. These optical phenomena have given, with great consistency, a height of 82 to 85 km.

6.1. Noctilucent Clouds

As early as 1934 Hoffmeister attempted to relate the occurrence of luminous bands in the night sky with ionospheric variations by assuming that both variations were due to sudden invasions of meteoric dust.

Paton (1951), reporting on true noctilucent clouds, considered that they were usually blue, indicating very small particle size, but that some portions had been known to turn white. This change was attributed to particle growth by condensation of water vapor on meteoric dust. A very comprehensive survey of all available information on noctilucent clouds was given by Ludlam in 1957. The spread in height was between 79 and 90 km, with the mean of 179 observations at 82.1 km. The particle size was in general too large to give a blue cloud by Rayleigh scattering. The temperature minimum at the inversion height, where the clouds are found, was considered to be too high to allow condensation of water vapor at the prevailing air pressure unless a very abnormal humidity condition was postulated. Once again, therefore, the material was considered to be dust. The specific height is attributed to solid material falling from above 82 km due to gravity, or rising from below the temperature inversion due to reradiation of solar energy to the surrounding air, with consequent upward movement of both air and particle. Noctilucent clouds have a considerable directed horizontal drift speed.

6.2. Scattered Sunlight

At dawn the sun progressively illuminates lower regions of the ionosphere, or the converse at dusk, while the earth remains in darkness. Two techniques have been used to observe the ionosphere at these times.

The first, giving surprising results, was carried out by Khvostikov and Sevcenko as long ago as 1936 in the Caucasus. Basically, their assumption was that a strongly ionized gas would affect the polarization of the diffused light, and that at any given moment at dusk the greater part of the diffused light proceeds from a relatively thin region. The polarization of the diffused light from the zenith was measured continuously, at 3,000 m above sea level, and discontinuities in the degree of polarization versus height observed. Due to unfavorable weather conditions, only seven curves were obtained, but these are just enough to indicate that similar heights were observed on different days. Five morning curves show heights of 95 and 135 km, and two evening curves indicate heights of 80, 115, and 150 km. (These results were obtained before the *E*-region was considered to be other than a single layer.)

The higher morning values were attributed to nighttime recombination. The results, admittedly, are no more than an indication of a method, but the technique does not appear to have been used since 1936. The method is quite simple, and in a suitable locality may well be worth further study, particularly as it can reveal small maxima of electron concentration above a larger maximum.

The second technique, due to Bigg in 1956, involves direct twilight scattering. He was able to show a small maximum in the scattered light at 81.1 ±5 km, and assumes it is due to a meteoric dust layer.

6.3. Airglow

The night sky radiates a weak continuum, together with a number of emission bands. In addition certain lines, especially of sodium, show a more prominent emission at twilight. The airglow, excluding the sodium and calcium twilight emission, will first be considered.

Many early results on the height of the airglow have been rendered obsolete by the work of Bates and Dalgarno (1953), who show that most mechanisms can only apply below 100 km; together with a fuller recognition of the experimental difficulties in this work, and the necessity to eliminate all light of astronomical origin.

Most work has been done on the green OI radiation of wavelength 5577 A, in the airglow. In 1955, St. Amand, Pettit, Roach, and Williams were able, by triangulation, to place the height at 80 to 199 km. In the same year Roach and Meinel listed the spread in heights of several airglow components. Each of the components occupied a different height zone, and the green OI line was found between 62 and 104 km. Elsasser and Siedentopf, in 1956, place the green OI line at 90 ±10 km, and Roach, Megill, Rees, and Marovich (1958) at about 100 km, agreeing reasonably with a rocket flight in 1956 (Berg et al.) where the peak luminosity was found at 90 to 95 km, and another flight in 1958 (Heppner and Meredith) where the radiation was observed only between 90 and 118 km, with a sharp lower boundary. Manring and Pettit (1956) find variations of the height with night and season, so that definite heights—using the accepted Van Rhyn method of reduction—are not possible at present.

Night NaD was found by Roach and Meinel between 108 and 129 km. This fairly wide spread is to some extent reinforced by Heppner and Meredith's rocket flight, where NaD was found primarily between 85 and 110 km, with a maximum at 93, but with a tail-off in distribution extending into the 130 to 150 km region.

In two papers Roach, Tandberg-Hansen, and Megill (1958 a, b) have reemphasized that the night airglow as seen by the green OI radiation is not uniform in its distribution, but is concentrated in cells or patches whose characteristic size is approximately 2,500 km in horizontal extent. During the period October–December 1956 the cells seemed to move, usually from north to south with a mean speed of about 100 m/sec. The authors, in the second paper, have decided that the apparent motion is due to actual transport of particles carried along by large-scale wind movements, and point out that the composite picture is generally similar to vortex cells in the troposphere. For a phenomenological description of the night airglow, including historical background, see Roach (1959).

6.4. Sodium and Calcium at Twilight

Hunten and Shepherd (1954) find a maximum sodium density at 85 ± 3 km, with an exponential decrease above and below this height. Hunten, in the following year, surveying two years' results on the height of maximum density of the sodium, found that the height remained constant within 1 or 2 km of 84.5 km, but that the intensity varies seasonally, and concluded from this that there may be transport of neutral sodium from polar regions in winter. Finally the work of Chamberlain, Hunten, and Mack (1958) supports the view that twilight emission is a resonance scattering effect, rather than a dissociation brought about by ultraviolet light. It is possible that the sodium travels up through the whole atmosphere from sea level. A latitude effect also exists. Correlation of abundance changes with the passage of meteor streams may yet be observed, but until it is there is no necessity to invoke a meteor origin for the sodium.

A. V. Jones (1956 and 1958), however, has observed with certainty twilight emission from ionized calcium, possibly correlating with meteor activity, particularly during the August Perseid shower. There is some evidence that the emission is concentrated in the 100- to 120-km region. This height happens to agree with the value calculated by Kaiser for maximum integrated meteor ionization, and the height of 100 to 110 km for the maximum of the night glow continuum determined by a rocket observation (Heppner and Meredith).

No author appears as yet to have given an explanation for the appreciably greater height of night sodium than the twilight sodium glow. As both sodium and calcium are constituents of meteors, identification of intensity variations in the night sodium—or even possibly in the twilight glow at lower height—may yet be found to be a function of meteor activity, similar to the calcium activity.

Heavy atomic ions, such as calcium, may also be introduced into the atmosphere following solar flares (Bailey 1957), and this could both complicate the variability of the twilight glow, and provide a temporary source of extra ionization.

7. Photoemissive Processes

The literature abounds with explanations of the production of free electrons by the interaction of selected solar radiations with specific upper atmosphere constituents. In conjunction with other theories explaining various recombination processes, these lead to the desired equilibrium concentrations of free electrons at specific heights. The field of study is an extremely difficult one, requiring as it does a combination of detailed knowledge of atomic processes, of the flux of incoming solar radiation, and of the exact components and physical conditions in the upper atmosphere. Many of these explanations have subsequently been disproved, and a new discovery, such as the existence of appreciable quantities of solar X-radiation, entirely altered the position. In view of this prevailing uncertainty, only brief mention will be made here of some recent views of electron production and decay in the lower ionosphere.

Chapman's theoretical treatment (1931) of the ionizing effect of monochromatic radiations of known intensity on particular atom species in an idealized atmosphere is still basic to most theories.

7.1. *E*-Region

Ionization at a true height of about 130 km was for some years considered to be due to photoionization of atomic oxygen by ultraviolet radiation ($\lambda > 910$ A, Nicolet 1952). By 1954, Bates regarded this process as accounting for the E_2 layer only, and reintroduced the photoionization of molecular oxygen as the main contributor to the E_1 layer, at the same time recognizing that X-rays could be of significance. New data for the absorption of radiation in the 850 to 1100 A band by O_2 and N_2 led Watanabe, Marmo, and Pressman (1955) to conclude that Lyman β could ionize O_2. Bates was thus supported, and the ultraviolet ionization of O_2 was not entirely rejected in favour of the newer X-ray theory of E_1 origin. By 1956, however, Bates had concluded that X-rays of about 40 A were *mainly* responsible for the *E*-region, and the theories of ultraviolet ionization of atomic oxygen, together with the longer wavelength X-ray reactions, were transferred to the F_1 and F_2 regions.

7.2. *D*-Region

A somewhat greater uniformity prevails in theories of the origin of the *D*-region. In 1945, Nicolet suggested that the causitive agent was the photoionization of nitric oxide, according to $NO + h\nu\ (> 9.5eV) \rightarrow NO^+ + e$ by Lyman α radiation (λ 1216 A) which is able to penetrate the atmosphere to a height of 70 km.

A considerably increased value for the ionization cross section of NO, obtained by Watanabe, Marmo, and Inn (1953), reinforced Nicolet's original suggestion. Nicolet (1954) arrived at the specific conclusion that the Lyman α photoionization of a concentration of NO of up to 10^8 molecules/cm^3 caused the *D*-region at a height of less than 80 km.

A model of the *D*-region using this reaction was next proposed by Mitra (1954), with an assumed NO distribution, and a maximum NO concentration approaching 2×10^{12} molecules/cm^3 at 85 to 95 km. A further assumption of a recombination model was necessary to give an electron distribution in agreement with that deduced from certain radio observations. Direct rocket measurements (discussed by Bates, 1956) give a relative volume abundance of NO of $\lesssim 2\times10^{-4}$. If the total atmospheric concentration of all atom species is taken as 8×10^{13}/cm^3 at 90 km, the NO concentration would be $<4\times10^9$/cm.^{3} The corresponding figures at 80 km are of the order 4.8×10^{14}/cm^3 and hence $< 2.4\times10^{10}$/cm^3 for NO. Thus the concentration proposed by Mitra is clearly greater than observed, but Nicolet's figures remain feasible. Rocket observations (Friedman and Chubb 1955) confirm the presence of Lyman α in the *D*-region, with solar X-rays contributing to the upper part.

Finally, Nicolet (1954) has introduced atmospheric motions, causing fluctuations in NO concentration, to account for the variations in the *D*-region ionization

7.3. Sudden Ionospheric Disturbances

Various radio methods have long shown with clarity a sudden increase in ionization at very low heights, down to 64 km, during a solar flare. As an example, Gregory (1958 b) presented an analysis of the effect of SID's on 1.75 mc reflections. In 7 cases out of 18 all echoes vanished during the disturbance; in 11 cases one height only (56 to 65 km) remained, and in 9 of these 11 this remaining height had not been present prior to the disturbance. He concludes that the occasional disappearance of all echoes indicates that absorption without reflection has been produced below 56 km.

It remained for rocket flights to confirm the increase in Lyman α and X-rays during such times as postulated by Bates and Massey (1951) and Piddington (1951). nhanced Lyman α intensity and X-radiation ~ 2 A have now been observed down to the 60 to 70 km region in a typical flare (Friedman and Chubb, 1955; Chubb et al. 1957). These observations lend support to the importance of both Lyman α and X-rays as normal ionizing agents in the lower ionosphere.

7.4. Recombination

The equilibrium electron concentration is also a function of the recombination rate. In this field theories do not as yet provide conclusive explanations. Direct (radiative) recombination, expressed in the simple equation $(dN/(dt)=q-\alpha N^2$ where N is the electron concentration, and q and α the effective rates of electron production and recombination respectively, does not agree with the observed rates of electron density change. The exponent 2, commonly used, is open to question (Rawer, 1956). Negative ions may play an important part below 80 km (Mitra and Jones, 1954), and much patient unraveling will be required to give a picture consistent with observed electron concentration values in the lower ionosphere.

8. Discussion of Survey Papers Dealing With the Lower Ionosphere [3]

1. Bracewell et al. (1951), **The Ionospheric Propagation of Low and Very Low Frequency Radio Waves Over Distances Less than 1,000 km.** This paper contains 54 references. Observed reflection heights are tabulated. One paragraph (5.2) discusses the evidence for multiple strata observed at 70 and 113 kc

2. Mitra (1951), **The D Layer of the Ionosphere.** In part I the author gives a résumé of the present state of knowledge concerning the D-layer, and in Part II speculates on the origin and structure of the region.

3. Kitchen, Pressey, and Tremellen (1953), **A Review of Present Knowledge of the Ionospheric Propagation of Very Low, Low, and Medium Frequency Waves.** Some sferics work is included, and recommendations are made for further detailed research.

4. Briggs and Spencer (1954), **Horizontal Movements in the Ionosphere.** A survey of results obtained by radio methods. The authors decide that there are both irregular and systematic (diurnal and seasonal) horizontal movements at all ionospheric levels, and that there is a tendency for velocity to increase with height. Also, the velocities increase with magnetic disturbance, especially at the higher heights. The paper ends with a summary of nonradio methods.

5. Weekes (1954), **The Physical State of the Upper Atmosphere.** The author starts with a general discussion of the problems and then discusses the following specific fields:

Composition, temperature and pressure of the atmosphere at different levels, results of rocket measurement of those quantities, measurements of wind and turbulence, and transport of ionization in the upper atmosphere. Many references are given.

6. Waynick (1955), **The Lowest Ionosphere.** The main properties of the region are surveyed, with the conclusion that most of the experimental evidence is in favor of at least one *D*-layer below *E*-region, with possible additional stratification of one form or another. A collection of curves from different sources is given showing the variation of recombination coefficient with height.

---

[3] Material in the following papers has been included, where applicable, in the general text.

7. Murgatroyd (1957), **Winds and Temperatures between 20 km and 100 km—a Review.** The author states that the measurement of winds is a more reliable way of calculating temperatures in the upper atmosphere than vice versa. He proposes a standard atmosphere to 100 km based almost entirely on wind measurements, which is applicable between 30° and 60° latitudes. Before much progress in the study of turbulence can be made, a knowledge of the wind structure in considerably greater detail is necessary. In addition, measurement of atmospheric composition, including ozone and water vapor at all possible levels, is necessary to allow studies of the radiation of heat energy.

9. Tables of Observed Heights

In an endeavor to determine whether any pattern of heights exists, all the relevant experimental results so far discussed have been collected in tables 1 and 2, with the exception of lowered heights recorded during solar flares.

The results given in table 2 reveal two facts. First, while a definite height may be obtained for a specific process, different classes of phenomena show their maxima at different heights. Secondly, some weak grouping of events in height ranges may be discerned. During the daytime three, or possibly four height groups contain the major proportion of the results. These are the belts 67 to 75, 80 to 90, 95 to 97, and possibly 110 to 113 km. At night only the two center groups remain, namely 80 to 87, and a somewhat wider 92 to 98.

The only nighttime results below 80 km are Rivault's sferics observations, giving a mean height of 75 km; and frequent vertical pulse echoes in winter down to 75 km obtained by Gregory. Rivault reports a lowering to 70 km during magnetic storms, and it may well be that Gregory's low height night results, including especially one observation at 67 km, are due to a similar cause.

10. Characteristics of an Acceptable Model of the Lower Ionosphere

As an outcome of the experimental data assembled above, it becomes possible to specify with reasonable certainty a number of conditions which must be met by any model purporting to explain the lower ionospheric radio observations. These characteristics are as follows:

(*a*) Probably the most consistent feature is the presence, night and day, of a reflection height of about 85 km at temperate latitudes. This height is roughly the same for all vertical incidence measurements from very low, through medium, to very high frequencies. The height appears to be associated with the temperature minimum (mesopause), and is the same height at which sharp maxima are found for the twilight NaD radiation, the occurrence of noctilucent clouds, and the twilight scattering of sunlight from dust.

(*b*) Notwithstanding (*a*), the effective reflection height calculated from *oblique* incidence results appears to fall considerably with increasing range at very low to medium frequencies.

(*c*) Reflections at vertical incidence for medium frequencies and above are usually weak and hardly ever blanketing.

(*d*) On a sweep-frequency record, retardation cusps are not apparent on progressing from one reflection level to the next one above.

(*e*) Reflections from the region should not be polarized according to either magnetoionic component alone, but should have polarization corresponding to a mixture of the two.

(*f*) Several reflection heights usually occur simultaneously.

(*g*) The individual heights below the 85-km region can remain constant for periods of many hours, but may be different on different days. Observation of the lowest heights in the region requires a very large system sensitivity.

(*h*) Heights below 80 km are usually observed in the daytime only, and most often in the winter. Winter days of unusually low recorded heights occur in groups of several consecutive days.

(*i*) All reflections exhibit fading. The fading rate should also increase with increasing magnetic disturbance.

(*j*) During some SID's a new reflection height, lower than those previously seen, should be observed at medium frequencies, together with a weakening or complete disappearance of the signals from greater heights.

11. Model A

The observations showing the tendency for wind shears to exist in the lower ionosphere suggest that the discrete heights observed by radio reflection may be explained entirely by scatter from the turbulence thus produced. As discussed by Gallet (1951 and 1955) and Wheelon (1957), turbulent regions may become visible to radio waves when a gradient of ambient ionization is also present. Therefore the following model is proposed:

(*a*) The air is especially turbulent at certain altitudes. The altitudes are not specified, but there must be several and they must have the diurnal and seasonal variations compatible with the experimental evidence.

(*b*) A rather simple profile of ambient electron density versus altitude is assumed to occupy the whole region, having diurnal and seasonal variations due to radiation from the sun, and also showing occasional distortion due to solar eruptions. A possible arrangement is shown diagrammatically in figure 1.

The shaded areas are intended to represent the height, thickness, and (by their length) intensity of the turbulent regions. The regions will be most readily "visible" in the radio sense when there is a sufficient gradient of the ambient electron density—as given by the slope of the profiles—in these regions.

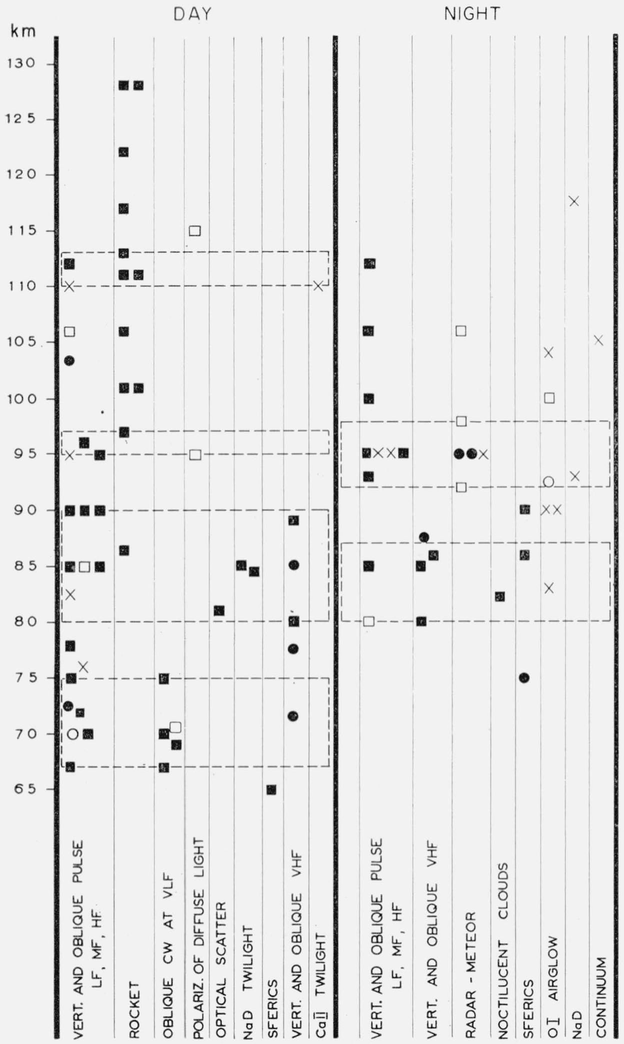
TABLE 1. *Observed heights*

Method	Authors	Year	Day	Night	Comments
			Km	*Km*	
Vert. pulse HF	Appleton and Piddington	1938	Broad peak at 110, nothing below 80.		
Vert. pulse HF sweep	Appleton, Naismith and Ingram.	1939	Partial at 90–100		Unrelated to Es.
Vert. pulse 100 kc	Helliwell	1949		84–106	Complicated split echoes.
Vert. pulse 100, 325 kc	Helliwell, Mallinkrodt and Kruse.	1951		90–130	Do.
Vert. pulse 100, 310, 2,400 kc	Helliwell	1952		93, 100, 106, 112	
Vert. pulse 150 kc	Lindquist	1953	85	95	
Vert. pulse LF sweep	Watts and Brown	1954	Layers between 70 and 100	90–100	
Vert. and oblique pulse MF	Naismith and Bramley	1951	70–75 equiv. vert. common at long range.		Day or night not specified. 85 occasionally, 106, 120–130.
Oblique pulse 300 kc	Watts	1952	∼70	≳80	
Vert. pulse inter-action 2,500 kc	Fejer	1955	72, 78		
Vert. pulse 1.4–4.0 Mc	Dieminger	1952	75–90 (winter)	95	More low level echoes in winter.
Vert. pulse 1.0, 1.4 Mc	Gnanalingam and Weekes	1952	90, 96, 112 (winter) 102–105 (summer)		75–80 on winter days of high absorption.
Vert. pulse 2.3 Mc	Gardner and Pawsey	1953	70–90 and *E*		Lowest height 55.
Vert. pulse 1.8 Mc	Gregory	1956	53, 67, 75 frequently, 85, 95 usually.	85	Lowest height 53. Low heights more common in winter. 85 always present.
Vert. pulse 1.8 Mc	Gregory	1958		Sometimes observed down to 75.	
Vert. pulse 2.3 Mc	Gregory	1959	62–90, 90 continuously		
CW oblique VLF	Weekes	1950	67, 75		Short range.
Do	Bain and Bracewell	1952	70		
Do	Budden	1953	69.1		
Do	Wait	1957	70		
Sferics	Rivault	1950		75 mean	70 or lower during magnetic storms.
Do	Caton and Pierce	1952		86	
Do	Hepburn and Pierce	1953	65	90	
Oblique pulse VHF	Forsyth, Currie and Vawter	1953		85	
Do	McKinley and Millman	1953	∼80	∼80	
Oblique CW and some pulse VHF.	Bailey, Bateman and Kirby	1955	75–80	85–90	Lowest day height 59, and several strata simultaneously.
Oblique pulse VHF	Pineo	1956	70–73, 89	86	
Vert. pulse 41 Mc	Bowles	1958	∼85		
Rocket transmitter	Lien et al.	1953	97, 111, 122		
Do	Seddon, Pickar and Jackson	1954	101, 113, 128		
Do	Jackson and Seddon	1958	101		=Es.
Do	Pfister and Ulwick	1958	106, 111, 117, 128		
Do	Seddon	1958	86.5		
Radar meteor echoes	Hey and Stewart	1947		95 mean	Day and night not usually distinguished. Majority of results night-observed.
Do	Millman and McKinley	1949		95 mean	
Do	McKinley and Millman	1949		90–100 fine structure	
Do	Millman	1957		92, 98, 106	
Noctilucent clouds	Ludlam	1957		79–90, peak at 82.1	
Polarization of diffused light	Khvostikov and Sevcenko	1936	95, 135 at dawn, 80, 115, 150 at dusk.		
Scattered light	Bigg	1956	81.1 ±5		
OI airglow (5577 A)	St. Amand et al.	1955		80–100	
Do	Roach and Meinel	1955		62–104	
Do	Elsasser and Siedentopf	1956		90 ±10	
Do	Berg et al.	1956		Peak intensity at 90–95	
Do	Heppner and Meredith	1958		90–118	Sharp lower boundary.
Do	Roach et al.	1958		∼100	
Night continuum	Heppner and Meredith	1958		100–110	
NaD twilight	Hunten and Shepherd	1954	85 ±3 peak		Exponential decrease on either side of peak.
Do	Hunten	1955	84.5		
CaII twilight	Jones	1956	100–120		
NaD	Roach and Meinel	1955		108–129	
Do	Heppner and Meredith	1958		85–110, peak at 93	Tails off to 150.

TABLE 2. *Grouping of heights*

	Definite result	*Less definite result*
Specific height	■	□
Mean of heights spread over <5 km	●	○
Mean of heights spread over >5 km		×

(No account has been taken of latitude or seasonal variations.)



The gradient must be dynamically stable, or the turbulence will, in time, destroy it.

Three electron density profiles, A, B, and C, are shown. Using A, the results of a normal day might be expected—reflections from several levels, of increasing gradient, and hence of increasing echo strength, with height. Profile B contains no electrons at the lower levels, corresponding to the disappearance of the lowest echoes at night. Profile C has a bulge below 80 km and might correspond to conditions during an SID, when the lowest reflection levels are enhanced and the other reflections weakened by increased absorption and the changes in slope along the profile.

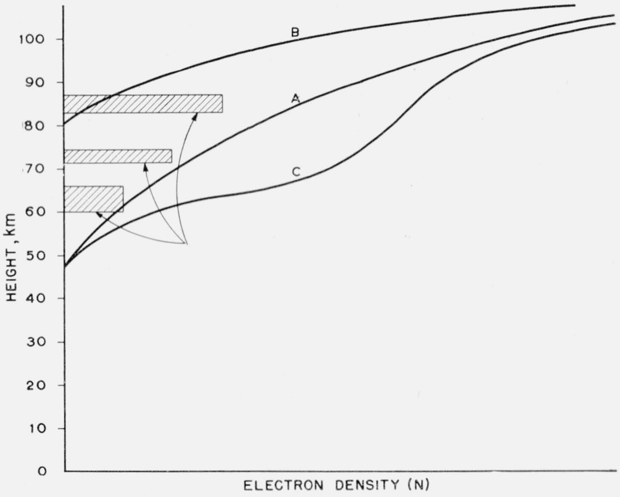


FIGURE 1. *Model of lower ionosphere showing strata of turbulence in relation to ambient electron density profiles.*

Arrows indicate regions of maximum turbulence.

It is suggested that this model is capable of fitting the experimental facts, at least qualitatively, as follows:

(*a*) Reflection heights at vertical incidence will be the same at all frequencies above the critical frequency for the ambient electron density at the reflection level. This is due entirely to the localization of the turbulent regions

(*b*) The lowest observable reflection height as determined by (*a*) will vary with the angle of incidence, since the lowest regions present more oblique aspects to the wave. Thus with increasing one-hop distances lower height echoes will gradually appear.

(*c*) At vertical incidence reflection will be partial at frequencies above the critical frequency for the reflection level. Plasma resonances due to the irregularities (see Herlofson 1951) may be observed near the critical frequency.

(*d*) On a sweep frequency exploration, the levels will be penetrated without retardation, provided penetration occurs well above the critical frequency of the reflection level.

(*e*) The reflected wave will not be split into ordinary and extraordinary components because of the absence of selective retardation (see (*d*) above).

(*f*) All reflection will fade, showing little or no specular component. The rate of fading will be a function of the meteorology of the region of reflection.

(*g*) Lowest heights are a function of both the turbulence and the ambient electron profiles. Because of this dual character, echo levels and intensities may vary from day to day.

This model can thus explain the radio observations of reflection heights at discrete levels without requiring extremely sharp gradients of the average electron density. It does not preclude the appearance of discrete reflections from real strata of ionization.

12. Model B

An alternative model might be constructed on the assumption of multiple Chapman processes. In this connection a model of the *D*- and *E*-regions calculated by Houston (1958), after a quantitative reappraisal of the ionizing radiations and the atmospheric constituents involved, is of interest. The only significant cause of the *D*-region was found to be the action of Lyman α radiation on NO, and it is probably coincidental that the computed ionization maximum at solar zenith was 83 km, in agreement with other mesopause phenomena.

Solar energies, particularly in the 100- to 1000-A region, are still largely unknown and the possibility of significant new processes being found cannot yet be ruled out. An attempt to include this portion of the spectrum has been made by Kallman (1957), who deduces therefrom a total distribution curve commencing at 88 km and rising smoothly to 105 km. Again, as is shown by the night OI airglow radiation, processes not directly involving ionization occur at fairly specific heights. Such processes may play an indirect part in daytime ionization control. Further, the resultant distribution even for a single layer may be far from a Chapman type due to variations in absorption of the band of wavelengths producing a particular photochemical reaction. Recent rocket studies, however, have led to a clarification of processes, and new discoveries are becoming less likely, especially at low heights. No model as yet shows any sign of multiple strata below 80 km.

A strong argument in favor of a photoemissive origin of such layers is the production of ionization at 64 km during a solar flare. Increased X-radiation causes this effect, so a smaller amount of radiation at this or slightly higher heights, while producing a smaller effect, should still be detectable with high system sensitivities. Even model A requires that the SID effect be of photoemissive origin.

Again, any layer under solar control should exhibit a considerable height change during the day due to $f(\chi)$ in the Chapman equation, where χ is the solar zenith distance. This is clearly shown in Houston's model, where the height of the maximum *D*-ionization rises from 83 to 100 km as χ changes from vertical to horizontal incidence. Diurnal height changes have been found at 16 kc (Straker, 1955), and the height of the lowest partial echo at MF shows a similar change (Gardner and Pawsey). It is possible that diurnal variations in the height of a single low stratum have not yet been closely looked for, but one point is quite clear. The electron concentrations, of the order of $1,000/\text{cm}^3$ or less, are far below the critical density required for classical MF or higher frequency reflections, and the phenomenon at those frequencies must be some form of scattering process.

Very sharp electron gradients can cause MF reflections, but the gradient values required are unlikely to be produced by solar effects alone. The simultaneous occurrence of several low strata, which have recently been observed in Germany, Australia, United States, New Zealand, and Antarctica, are surprisingly constant in height with time if the visual meteor trail turbulence observations of Liller and Whipple are accepted. The opposite case for stratified turbulence, however, appears from various radio echo experiments (sec. 4.1(a)). Consequently no firm conclusion can as yet be reached on the significance of photoemissive processes in the very low ionosphere.

13. Conclusions and Recommendations for Further Work

The authors conclude that the lower ionosphere exhibits the property of stratification as evidenced by all the available experimental results at medium and higher radiofrequencies. The fact that the properties of the region affecting low and very low frequencies may be explained by simpler structures does not appear to preclude a more complex structure, since the summation effects of long radio wavelengths would be expected to conceal details having physical dimensions much smaller than one wavelength. It is suggested, however, that rather subtle anomalies of long wave propagation may exist which will require more detailed knowledge of the fine structure of the region for their interpretation. In this respect, observations at a single low frequency have probably reached the stage of diminishing returns, and finer probing, such as is given by high power narrow pulsed HF systems will be necessary to reveal further details.

Evidence is strong for the accumulation of dust, and of sodium and probably calcium atoms at the temperature minimum at about 85 km in temperate latitudes. This accumulation may or may not be the cause of either an ionization maximum or a steep gradient at this height, but at least a partial reflection at MF is always obtained, provided the sensitivity is high enough. Beyond this fact it can only be said that strata exist over the region 54 to 130 km, without any obvious constancy of height or of height separation. There is no series of preferred heights.

Any further physical explanation of the fine structure can only be guessed at in the absence of extensive knowledge of its characteristics. It seems evident, out of all the material consulted, that only two or three experiments have given unambiguous information on the basic ionospheric quantities in the region. Acceptance of the evidence for stratification automatically casts doubt upon the meaning of the radio height results. The results from most pulse-type radio probing techniques in this region may be explained by any or all of the following: electron concentration maxima, electron gradients, or zones of turbulence.

Direct probing by rockets is one method which does provide the required electron profiles. If possible, it would be highly desirable to carry out a series of electron profile observations capable of recording the weak electron concentrations in the lower ionosphere, at a fixed site. If this is not possible, rockets could at least be used in conjunction with other cheaper experiments in an attempt to check the accuracy of the other methods, as has been done with satisfactory results for the upper ionosphere in conjunction with ordinary ionosondes.

Two nonrocket radio probing methods are reasonably unambiguous. One, due to Fejer (1955), measures wave interaction in the ionosphere, but requires large radiated power. The other, by Gardner and Pawsey (1955) has the very interesting feature that, instead of the results being uncertain because of the presence of fine structure, the method actually requires and uses partial reflections from the region to deduce the electron density at various heights. To lend emphasis to this method, which has not been fully exploited in lower ionosphere studies, a brief description follows.

Gardner and Pawsey found that the polarization of echoes returned from the *D*-region was elliptical, but with the sense of rotation of an extrordinary wave. This was compatible with partial reflection from "under-dense" clouds of ionization for a frequency above the gyrofrequency. Upon examining the magnetoionic formula for the refractive index they found that, to a good approximation, the ratio of ordinary to extraordinary polarization of the partial reflection coefficient was almost solely a function of the collision frequency at the reflecting region. The differential absorption between the two components of the wave from a reflecting region was almost solely a function of the electron density at each element of the path below the region for a fixed collision frequency. Therefore, by assuming a reasonable variation of collision frequency with height, the effect of the partial reflection at the discontinuity could be removed from the resultant received wave, and a curve of differential absorption against height could be plotted by measuring the polarization of the received wave from all heights which returned usable echoes. The slope of that curve, together with the value of collision frequency at each point, provided a measure of electron density at the various heights.

An assumption of the values of collision frequency was necessary, as mentioned above, but Gardner and Pawsey were also able to measure it near the bottom of the reflecting region by assuming no absorption had affected the shortest range echoes. The polarization measurement then represented only the ratio of the partial reflection coefficients which, as noted above, resulted in a determination of the collision frequency at that level. An extrapolation of this collision frequency to greater heights was done by assuming an arbitrary law of its variation.

Specific Recommendations for Future Radio Experiments

1. Confirmation of the accuracy of the Gardner and Pawsey polarization method is desirable before it is given extended use. This confirmation could be achieved by a Gardner and Pawsey experiment combined with simultaneous rocket electron profile measurements. It is very necessary to determine whether or not all concentration "blobs" of electrons are of less than critical density, particularly as Gregory at times obtains a high reflection coefficient which might indicate an over-dense condition. Such a condition would affect the polarization and invalidate the method. An alternate method of checking would be to duplicate the Gardner and Pawsey method at two reasonably close frequencies both a little above the gyrofrequency. If the same profile is obtained at the two frequencies, then the electron density of the scattering blobs must be considerably below the critical density.

2. A single MF vertical pulse equipment should be run continuously—without any inserted attenuation—through the dawn, daytime and dusk period to look for any systematic height change associated with a specific stratum. This should give evidence bearing on the photoemissive origin or otherwise of the reflective region.

3. The synoptic behavior of all the lower strata is virtually an unexplored field. Since VHF forward scatter communication has been shown to be directly related to these strata, seasonal and geographic studies are necessary to allow the optimum design of forward scatter aerials.

4. The resolution of the height and width of strata by vertical pulse techniques is dependent on the aerial beam width. It would be desirable either to alter a beam width, or to use two experiments together—say 2 and 40 Mc—with considerably different beam widths, to determine the extent of range spread introduced by off-vertical directions. Once this had been determined, experiments could then be designed to examine particular heights for horizontal motion at low heights, and to investigate the relationship between turbulence and height.

5. Further studies are required of the apparent lowering of strata heights during magnetically disturbed periods. Again rocket flights at such a period, together with quiet period control flights, should reinforce the vertical pulse techniques in determining the electron profiles at such times.

6. It would appear that the 95-km lower *E*-ledge is created by the action of Lyman β radiation on O_2 (Houston 1958), and the 83-km region is attributed to Lyman α. If it is assumed that the intensities of both solar radiations change together, then some parallelism should be evident in the behavior of the two regions. Parallelism of behavior of *any* lower region with the 95-km daytime region would be evidence favoring a photoemissive origin of the lower region.

14. References

Appleton, E. V., On some measurements of the equivalent height of the atmospheric ionized layer, Proc. Roy. Soc. A. **126**, 542 (1930).

Appleton, E. V., Naismith, K., and Ingram, L. J., The critical frequency method of measuring upper atmospheric ionization, Proc. Phys. Soc. (London) **51,** 81 (1939).

Appleton, E. V. and Piddington, J. H., The reflection coefficients of ionospheric regions, Proc. Roy. Soc. A. **164,** 467 (1938).

Appleton, E. V. and Piggott, W. R., Ionospheric absorption measurements during a sunspot cycle, J. Atmospheric Terrest. Phys. **5,** 141 (1954).

Bailey, D. K., Disturbances in the lower ionosphere observed at VHF following the solar flare of 23 February 1956 with particular reference to auroral zone absorption, J. Geophys. Research **62,** 431 (1957).
Bailey, D. K., Bateman, R. and Kirby, R. C., Radio propagation at VHF by scattering and other processes in the lower ionosphere, Proc. IRE **43,** 1,181 (1955).
Bain, W. C., Observations on the propagation of very long radio waves reflected obliquely from the ionosphere during a solar flare, J. Atmospheric Terrest. Phys. **3,** 141 (1953).
Bain, W. C. and Bracewell, R. N., An explanation of radio propagation at 16 kc in terms of two layers below *E* Layer, J. Atmospheric Terrest. Phys. **2,** 216 (1952).
Banerji, R. B., Heights of irregularities giving rise to the fading of 150 kc waves, J. Geophys. Research **60,** 431 (1955).
Bates, D. R., The formation of the *E*-layer, Proc. Mixed Commission on the Ionosphere, **82,** (Brussels 1954).
Bates, D. R., Recombination in the ionosphere, Solar Eclipses and the Ionosphere, Spec. supp. to J. Atmospheric Terrest. Phys. **6,** 191 (1956).
Bates, D. R., Formation of the ionized layers, Solar Eclipses and the Ionosphere, Spec. supp. to J. Atmospheric Terrest. Phys. **6,** 184 (1956).
Bates, D. R. and Dalgarno, A., The altitudes of the luminous layers of the earth's atmosphere, J. Atmospheric Terrest. Phys. **4,** 122 (1953).
Bates, D. R. and Massey, H. S. W., The negative ion concentration in the lower ionosphere, J. Atmospheric Terrest. Phys. **2,** 1 (1951).
Benner, A. H., Grace, C. H., and Kelso, J. M., Polarization of low frequency radio waves reflected from the ionosphere, Proc. IRE **38,** 951 (1950).
Berg, O. E., Koomen, M., Meredith, L., and Scolnik, R., The altitude of the (OI) 5577 A line in the night airglow measured from a rocket, J. Geophys. Research **61,** 302 (1956).
Bigg, E. K., Detection of atmospheric dust and temperature inversions by twilight scattering, Nature **177,** 77 (1956).
Booker, H. G., Turbulence in the ionosphere with application to meteor trails, radio star scintillations, auroral radio echoes, and other phenomena, J. Geophys. Research **61,** 673 (1956).
Bowhill, S. A., The fading of radio waves of frequencies between 16 and 2,400 kc, J. Atmospheric Terrest. Phys. **8,** 129 (1956).
Bowhill, S. A., Ionospheric irregularities causing random fading of very low frequencies, J. Atmospheric Terrest. Phys. **11,** 91 (1957).
Bowles, K. L., Observation of vertical incidence scatter from the ionosphere at 41 mc, Phys. Rev. Letters **1,** 454 (1958).
Bracewell, R. N., Theory of formation of an ionospheric layer below *E* layer based on eclipse and solar flare effects at 16 kc/sec, J. Atmospheric Terrest. Phys.**2,** 226 (1952).
Bracewell, R. N., Budden, K. G., Ratcliffe, J. A., Straker, T. W., and Weekes, M. A., The ionospheric propagation of low and very low frequency radio waves over distances less than 1,000 km, Proc. IEE Part III **98,** 221 (1951).
Briggs, B. H., An investigation of certain properties of the ionosphere by means of a rapid frequency change experiment, Proc. Phys. Soc. B. **64,** 255 (1951).
Briggs, B. H. and Spencer, M., Horizontal movements in the ionosphere, Rep. on Prog. in Phys. **17,** 245 (1954).
Budden, K. G., The propagation of VLF radio waves to great distances, Phil. Mag. **44,** 504 (1953).
Budden, K. G., The numerical solution of differential equations governing reflection of long radio waves from the ionosphere, Proc. Roy. Soc. A. **227,** 516 (1955).

Caton, P. G. F. and Pierce, E. T., The waveforms of sferics, Phil. Mag. **43,** 393 (1952).
Chamberlain, J. W., Hunten, D. M. and Mack, J. E., Resonance scattering by atmospheric Na.—IV, J. Atmospheric Terrest. Phys. **12,** 153 (1958).
Chapman, S., The absorption and dissociative or ionizing effect of monochromatic radiation in an atmosphere on a rotating earth, Proc. Phys. Soc. **43,** 26 (1931).
Chubb, T. A., Friedman, H., Kreplin, R. W., and Kupperian, J. E. Jr., Rocket observation of X-ray emission in a solar flare, Nature **179,** 861 (1957).

Davids, N. and Parkinson, R. W., Wave solutions for critical and near critical coupling conditions in the ionosphere, J. Atmospheric Terrest. Phys. **7,** 173 (1955).
Deb, S., Origin of the *D* layer, Indian J. Phys. **14,** 89 (1940).
Dieminger, W., On the causes of excessive absorption in the ionosphere on winter days, J. Atmospheric Terrest. Phys. **2,** 340 (1952).
(See also Dieminger, W. and Hofmann-Heyden, A. E. Naturwissenshaften **39,** 84 (1952).
Dubin, M., Meteor ionization in the *E* region, Meteors, Spec. supp. to J. Atmospheric Terrest. Phys. **2,** 111 (1955).

Eckersley, T. L., Observations of scatter clouds, Nature **162,** 24 (1948).
Edwards, H. D., Bedinger, J. F., Manring, E. R., and Cooper, C. D., Emission from a sodium cloud artificially produced by means of a rocket, The Airglow and the Aurorae (Pergamon Press, 122, 1955).
Ellyett, C. D., Echoes at *D* heights with special reference to the Pacific Islands, Terrestrial Magnetism and Atmospheric Elec. **52,** 1 (1947).
Elsasser, H. and Siedentopf, H., The height of emission of the 5577 line of the airglow as observed on the Jungfraujoch, J. Atmospheric Terrest. Phys. **8,** 222 (1956).
Evans, S., Scale heights and pressures in the upper atmosphere from radio echo observations of meteors, Monthly Notices Roy. Astron. Soc. **114,** 63 (1954).
Evans, S., Atmospheric pressures and scale heights from radio echo observations of meteors, Meteors, Spec. supp. to J. Atmospheric Terrest. Phys. **2,** 86 (1955).

Fejar, J. A., The interaction of pulsed radio waves in the ionosphere, J. Atmospheric Terrest. Phys. **7,** 322 (1955).
Fleagle, R. G., Inferences concerning the dynamics of the mesopause, J. Geophys. Research **63,** 137 (1958).
Forsyth, P. A. Currie, B. W., and Vawter, F. E., Scattering of 56 mc radio waves from the lower ionosphere, Nature **171,** 35 (1953).
Friedman, H. and Chubb, T. A., Solar X-ray emission and the height of the *D* layer during radio fadeout, The Physics of the Ionosphere (Pergamon Press, 58, 1955).

Gallet, R. M., The nature of the sporadic *E* layer and turbulence in the upper atmosphere, C. R. Acad. Sci. **233,** 1649 (1951).
Gallet, R. M., Aerodynamical mechanisms producing electronic density fluctuations in turbulent ionized layers, Proc. IRE **43,** 1240 (1955).
Gardner, F. F. and Pawsey, J. L., Study of the ionospheric *D* region using partial reflections, J. Atmospheric Terrest. Phys. **3,** 321 (1953).
Gibbons, J. J. and Nertney, R. J., Wave solutions, including coupling, of ionospherically reflected long radio waves for a particular *E* region model, J. Geophys. Research **57,** 323 (1952).
Gnanalingam, S. and Weekes, K., Weak echoes from the ionosphere with radio waves of frequency 1.42 mc, Nature **170,** 113 (1952).
Gnanalingam, S. and Weekes, K., *D* region echoes observed with a radio wave of frequency 1.4 mc, The Physics of the Ionosphere (Pergamon Press, 1955).
Greenhow, J. S., Characteristics of radio echoes from meteor trails: III. The behaviour of the electron trails after formation, Proc. Phys. Soc. B, **65,** 169 (1952).
Greenhow, J. S., Systematic wind measurements at altitudes of 80–100 km using radio echoes from meteor trails, Phil. Mag. **45,** 71 (1954).
Greenhow, J. S. and Neufeld, E. L., Diurnal and seasonal wind variations in the upper atmosphere, Phil. Mag. **46,** 549 (1955).
Greenhow, J. S. and Neufeld, E. L., The height variation of upper atmospheric winds, Phil. Mag. (8th Ser.) **1,** 1157 (1956).
Gregory, J. B., Ionospheric reflections from heights below the *E* region, Australian J. Phys. **9,** 324 (1956).

Gregory, J. B., The relation of forward scattering of very high frequency radio waves to partial reflection of medium frequency waves at vertical incidence, J. Geophys. Research **62,** 383 (1957).

Gregory, J. B. (a), The mesopause region of the ionosphere, Nature **181,** 753 (1958).

Gregory, J. B. (b), Medium frequency observations of the lower ionosphere during sudden disturbances, J. Geophys. Research **63,** 273 (1958).

Gregory, J. B., (Private communication 1959).

Helliwell, R. A., Ionospheric virtual height measurements at 100 kc, Proc. IRE **37,** 887 (1949).

Helliwell, R. A., Sporadic *E* stratification and correlation with low frequency soundings, Trans. IRE, PGAP **3,** 140 (1952).

Helliwell, R. A., Mallinkrodt, A. J., and Kruse, F. W. Jr., Fine structure of the lower ionosphere, J. Geophys. Research **56,** 53 (1951).

Hepburn, F. and Pierce, E. T., Atmospherics with VLF components, Nature **171,** 837 (1953).

Heppner, J. P. and Meredith, L. H., Nightglow emission altitudes from rocket measurements, J. Geophys. Research **63,** 51 (1958).

Herlofson, N., The theory of meteor ionization, Rep. on Prog. in Phys. **11,** 444, (1948).

Herlofson, N., Plasma resonance in ionospheric irregularities, Arkiv För Fysik **3,** 247 (1951). (See also Tonks, L., Phys. Rev. **38,** 1219, 1931)

Hey, J. A. and Stewart, G. S., Radar observations of meteors, Proc. Phys. Soc. **59,** 858 (1947).

Hoffmeister, C., Cosmic influence on the upper strata of the atmosphere, Naturwiss. **22,** 458 (1934).

Hopkins, H. G. and Reynolds, L. G., An experimental investigation of short distance ionospheric propagation at low and very low frequencies, Proc. IEE Part III **101,** 21 (1954).

Houston, R. E., The effect of certain solar radiations on the lower ionosphere, J. Atmospheric Terrest. Phys. **12,** 225 (1958).

Hunten, D. M., Season variations of twilight Na emission, The Airglow and the Aurorae, Spec. Supp. to J. Atmospheric Terrest. Phys. **5,** 114 (1955).

Hunten, D. M. and Shepherd, G. G., A study of sodium at twilight: II Observations on the distribution, J. Atmospheric Terrest. Phys. **5,** 57 (1954).

Jackson, J. E., Measurements in the *E* layer with the Navy Viking rocket, J. Geophys. Research **59,** 377 (1954).

Jackson, J. E. and Seddon, J. C., Ionosphere electron density measurements with the Navy Aerobee-Hi rocket, J. Geophys. Research **63,** 197 (1958).

Jones, A. V., CaII emission lines in the twilight spectrum, Nature, **178,** 276 (1956).

Jones, A. V., Calcium and oxygen in the twilight airglow, Annal. die Geophysique **14,** 179 (1958).

Jones, I. L., The height variation of drift in the *E* Region, J. Atmospheric Terrest. Phys. **12,** 68 (1958). (See also special Supplement to J. Atmospheric Terrest. Phys. **12,** Part II, 20, 1957).

Jones, R. E., Millman, G. H., and Nertney, R. J., The heights of ionospheric winds as measured at long radio wavelengths, J. Atmospheric Terrest. Phys. **3,** 79 (1953).

Kaiser, T. R., Radio echo studies of meteor ionization, Phil. Mag. Supp. **2,** 495 (1953).

Kallman, H. K., Electron distribution in a new model of the ionosphere, Special Supp. J. Atmospheric Terrest. Phys. **82** (1957) *Pergamon Press.*

Khvostikov, I. A. and Sevcenko, A. N., Application of the polarimetric method in the study of the structure of the upper layers of the atmosphere, Compt. rend. acad. sci. U.R.S.S. **IV,** No. 8, 359 (1936).

Kilpatrick, E. L. (Private communication 1957).

Kitchen, F. A., Pressey, B. G., and Tremellen, K. W., A review of present knowledge of the ionospheric propagation of very-low, low, and medium frequency waves, Proc. IEE, Pt. 3 **100,** 100 (1953).

Landmark, B., Echoes from the lower ionosphere during polar blackouts, J. Atmospheric Terrest. Phys. **12,** 79 (1958).

Lien, J. R., Marcou, R. J., Ulwick, J. C., McMorrow, D. R., Linsford, D. B., and Haycock, O. C., Bifurcation in the *E* region, Phys. Rev. **92,** 508 (1953).

Liller, W. and Whipple, F. L., High altitude winds by meteor-train photography, Rocket Exploration of the Upper Atmosphere. Spec. Supp. to J. Atmospheric Terrest. Phys. **I,** 112 (1954).

Lindquist, R., An interpretation of vertical incidence equivalent height versus time recordings at 150 kc, J. Atmospheric Terrest. Phys. **4,** 10 (1953).

Ludlam, F. H., Noctilucent clouds, Tellus **9,** 341 (1957).

Manning, L. A., Peterson, A. M., and Villard, O. G., Ionospheric wind analysis by meteoric echo techniques, J. Geophys. Research **59,** 47 (1954).

Manring, E. R. and Pettit, H. B., Observations of the OI 5577 nightglow at Sacramento Peak, New Mexico, February through June 1955, The Airglow and the Aurorae, Supp. to J. Atmospheric Terrest. Phys. **5,** 29 (1955).

Maxwell, A., Turbulence in the upper ionosphere, Phil. Mag. **45,** 1,247 (1954).

McKinley, D. W. R. and Millman, P. M., A phenomenological theory of radar echoes from meteors, Proc. IRE **37,** 364 (1949).

McKinley, D. W. R. and Millman, P. M., Long duration echoes from the aurora, meteors and the ionosphere, Can. J. Phys. **31,** 171 (1953).

Millman, P. M. (Private communication 1957).

Millman, P. M and McKinley, D. W. R., Three-station radar and visual triangulation of meteors, Sky and Telescope, 8 (March 1949).

Mitra, A. P., The *D*-layer of the ionosphere, J. Geophys. Research **56,** 373 (1951).

Mitra, A. P., A tentative model of the equilibrium height distribution of NO in the high atmosphere and the resulting *D*-layer, J. Atmospheric Terrest. Phys. **5,** 28 (1954).

Mitra, A. P. and Jones, R. E., Recombination in the lower ionosphere, J. Geophys. Research **59,** 391 (1954).

Murgatroyd, R. J., Winds and temperatures between 20 km and 100 km—a review, J. Roy. Met. Soc. **83,** 417 (1957).

Naismith, R. and Bramley, E. N., Time delay measurements on radio transmissions, Wireless Engr. **28,** 271 (1951).

Nertney, R. J., Comments concerning the paper by Helliwell et al., J. Geophys. Research **56,** 449 (1951).

Nertney, R. J., The lower *E* and *D*-region of the ionosphere as deduced from long radio wave measurements, J. Atmospheric Terrest. Phys. **3,** 92 (1953).

Nicolet, M., Action of solar radiation in the upper atmosphere, Annal. die Geophysique **8,** 141 No. 2 (1952).

Nicolet, M., The *D* layer and nitric oxide, Proc. Mixed Commission on the Ionosphere, Brussels —, 40 (1954).

Öpik, E. J., Problems in the physics of meteors, Amer. J. Phys. **26,** 70 (1958).

Parkinson, R. W., The night-time lower ionosphere as deduced from a theoretical and experimental investigation of coupling phenomena at 150 kc/s, J. Atmospheric Terrest. Phys. **7,** 203 (1955).

Parkinson, R. W., The fading periods of the *E*-region coupling echo at 150 kc/s, J. Atmospheric Terrest. Phys. **8,** 158 (1956).

Paton, J., Auroras and luminous night clouds, Nature **168,** 487 (1951).

Pfister, W. and Ulwich, J. C., The analysis of rocket experiments in terms of electron-density distributions, J. Geophys. Research **63,** 315 (1958).

Piddington, J. H., The modes of formation of the ionospheric layers, J. Geophys. Research **56,** 409 (1951).

Pineo, V. C., Oblique incidence measurements of the heights at which ionospheric scattering of VHF radio waves occurs, J. Geophys. Research **61,** 165 (1956).

Poeverlein, H., Low frequency reflection in the ionosphere—I, J. Atmospheric Terrest. Mag. **12,** 126 (1958); Low frequency reflection in the ionosphere—II, J. Atmospheric Terrest. Mag. **12,** 236 (1958).

Porter, J. G., An analysis of British meteor data, Mon. Not. Roy. Astron. Soc. **104,** 257 (1944).

Prentice, J. P. M., Meteors, Rep. on Prog. in Phys. **XI,** 389 (1948).

Ratcliffe, J. A. and White, E. L. C., The effect of the earth's magnetic field on the propagation of short wireless waves, Phil. Mag. **16,** 125 (1933).

Rawer, K., A critical survey of eclipse information on recombination data, Solar Eclipses and the Ionosphere, Spec. Supp. to J. Atmospheric Terrest. Mag. **6,** 198 (1956).

Rivault, R., The microstructure of atmospherics. Ionospheric and meteorological applications of those of type 4, C. R. Acad. Sci. **230,** 1846 (1950).

Roach, F. E., The night airglow, Proc. IRE **47,** 267 (1959).

Roach, F. E. and Meinel, A. B., The height of the night glow by the van Rhyn method, Astrophys. J. **122,** 530 (1955).

Roach, F. E., Megill, L. R., Rees, M. H., and Marovich, E., The height of night glow 5577; J. Atmospheric Terrest. Phys. **12,** 171 (1958).

Roach, F. E., Tandberg-Hansen, E., and Megill, L. R. (a), The characteristic size of airglow cells, J. Atmospheric Terrest. Phys. **13,** 113 (1958).

Roach, F. E., Tandberg-Hansen, E., and Megill, L. R. (b), Movements of airglow cells, J. Atmospheric Terrest. Phys. **13,** 122 (1958).

Seddon, J. C., Differential absorption in the *D* and lower *E* regions, J. Geophys. Research **63,** 209 (1958).

Seddon, J. C., Pickar, A. D., and Jackson, J. E., Continuous electron density measurements up to 200 km, J. Geophys. Research **59**, 513 (1954).

St. Amand, P., Pettit, H. B., Roach, F. E., and Williams, D. R., On a new method of determining the height of the airglow, J. Atmos. Terr. Phys. **6**, 189 (1955).

Straker, T. W., The ionospheric propagation of radio waves of frequency 16 kc/s over short distances, Monograph No. 114, Inst. Elec. Engrs. (London, 1955).

Thomas, J. A. and Burke, M. J., Motion of the night-time Es region at Brisbane, Australian J. Phys. **9**, 440 (1956).

Wait, J. R., The mode theory of VLF ionospheric propagation for finite ground conductivity, Proc. IRE **45**, 760 (1957).

Wait, J. R., An extension to the mode theory of VLF Ionospheric propagation, J. Geophys. Research **63**, 125 (1958).

Wait, J. R. and Perry, L. B., Calculations of ionospheric reflection coefficients at very low frequencies, J. Geophys. Research **62**, 43 (1957).

Watanabe, K., Marmo, F., and Inn, E. C. Y., Formation of the *D* layer, Phys. Rev. **90**, 155 (1953).

Watanabe, K., Marmo, F. F., and Pressman, J., Formation of the lower ionosphere, J. Geophys. Research **60**, 513 (1955).

Watts, J. M. (a), A note on the polarization of low frequency ionosphere echoes, J. Geophys. Research **57**, 287 (1952).

Watts, J. M. (b), Oblique incidence propagation at 300 kc using the pulse technique, J. Geophys. Research **57**, 487 (1952).

Watts, J. M. and Brown, J. N., Effects of ionosphere disturbances on low frequency propagation, J. Geophys. Research **56**, 403 (1951).

Watts, J. M. and Brown, J. N., Some results of sweep frequency investigation in the low frequency band, J. Geophys. Research **59**, 71 (1954).

Waynick, A. H., The lowest ionosphere, Physics of the Ionosphere, Physical Soc. (1955).

Weekes, K., The ground interference pattern of very low frequency radio waves, Proc. IEE, Part III **97**, 100 (1950).

Weekes, K., The physical state of the upper atmosphere, J. Roy. Meteorol Soc. **80**, 2 (1954).

Weiss, A. A., Radio echo observations of meteors in the southern hemisphere, Meteors, Spec. Supp. to J. Atmospheric Terrest. Phys. II 195 (1955).

Whale, H. A., Fine structure of the ionospheric region *E*, J. Atmospheric Terrest. Phys. **1**, 233 (1951).

Wheelon, A. D., Diurnal variations of signal level and scattering heights for VHF propagation, J. Geophys. Research **62**, 255 (1957).

Whipple, F. L., Results of rocket and meteor research, Bull. Am. Meteorol. Soc. **33**, 13 (1952).

BOULDER, COLO. (Paper 63D2-13)