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THE DISTRIBUTION OF ELECTRONS IN THE LOWER AND MIDDLE IONOSPHERE

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Abstract

A review of current knowledge of the distribution of electrons in the D, E and lower F regions of the ionosphere is presented. Particular emphasis is put on advances made during the triennium (1960-1963). Noteworthy is the increase in the amount of data available on the electron density profile in the D region from ground-based and rocket experiments. Also, the shape of the height profile of electrons in the E and lower F region has been significantly refined through the use of improved vertical sounders and by an increasing number of "in situ" observations. Information has been obtained by means of rocket experimentation on the nature of the ionization structures responsible for certain types of sporadic E.

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Introduction

This paper summarizes progress that has been made in understanding the distribution of electrons in the lower and middle ionosphere. In the case of the D and E regions, significant new observations reported in the last three to four years are reviewed and a brief account is given of progress in improving our understanding of the processes controlling the structure and behavior of the normal electron density profile in these regions. Recent rocket observations revealing the ionozation structures thought to be responsible for sporadic E are presented and mechanisms that have been postulated for producing these ionization gradients are discussed. After a review of an outline theory of the F region, as given in 1959, recent extensions, elaborations, and modifications are summarized. Only the sub-peak F region is considered, since the higher portions of the electron density profile are discussed in a companion paper by J. H. Chapman.

THE D REGION

Though the D region is the lowest of the ionospheric regions and therefore, in principle, the most accessible, our understanding of it has increased rather slowly. This is due in large part to the difficulty of applying conventional ground-based radio sounding techniques to the D region because of the strong radio wave absorption suffered by the exploring signals. Also, many of the direct measurement techniques used for rocket exploration of the E and F regions of the ionosphere are not suited to D-region studies either because of the low electron density or the high neutral gas density or both.

Nevertheless, within the last three to four years, a significant quantity of observational information on the D region has been accumulated. In the main, three different ground-based techniques, along with an increasing number of rocket experiments, have been used to obtain these data. The three indirect techniques involve cross modulation, partial reflections and radio wave absorption experiments.

The cross modulation experiment, first introduced by Fejer (1955), makes use of a powerful "disturbing" transmitter to heat the lower ionosphere, with a second transmitter employed to determine the amount of heating that has been introduced. Measurements of the change in amplitude of the exploring radio wave due to the heating, permit determination of the electron density and, with less accuracy, the collision frequency in the D region. Recently, interaction experiments have been pursued most actively by the Norwegian Defence

Research Establishment group (Landmark and Lied 1960; Barrington and Thrane 1962; Barrington, Thrane and Bjelland 1963; Piggott and Thrane 1963) though some work was reported in 1960 and 1961 by the Geophysical Institute of the University of Alaska (Rumi 1960, 1961). The results coming out of these experiments will be combined with other pertinent observations and summarized in a later section of this paper.

A second ground-based technique for D-region studies was developed by Gardner and Pawsey (1953) and has since been used extensively by Belrose of the Canadian Defence Research Telecommunications Establishment (Belrose 1961; Belrose and Cetiner 1962; Belrose 1963a and 1963b), and by Gregory (1961) and, in a modified version (Gnanalingham 1954) by Titheridge (1962a) of New Zealand. This experiment depends upon the existence of discrete irregularities in the lower ionosphere from which, given sufficiently high transmitter power, partial reflections can be obtained. Measuring the ratio of the amplitudes of the reflected ordinary and extraordinary magnetoionic components as a function of height allows determination of the electron density at the height of reflection in terms of an assumed collision frequency profile. Results of D-region profile studies made using the partial reflection technique will also be given later.

A third indirect technique for investigating the D region during disturbed periods has been perfected recently by Parthasarathy, Lerfald and Little (1963). This experiment is based on simultaneous measurements of ionospheric absorption on several frequencies using the riometer technique and also involves an assumed model of the height variation of electron collision frequency. In the initial studies, absorption measurements on four frequencies between 10 and 50 Mc/s were used to determine representative D-region electron density profiles during several polar cap absorption events.

Other ground-based techniques have also provided information on the properties of the D region. These include oblique and steep incidence recordings of the phase and amplitude of VLF and LF radio transmissions. The early work of the Cambridge and Penn. State groups in this field, and the theoretical studies of Wait have been particularly noteworthy. Specially designed low frequency ionosondes have also been used by Watts and Hough in the United States and Elling in South West Africa. Recently, Paulson, Gossard and Moler (1963) of the United States Navy Electronics Laboratory have reported the development of a near vertical incidence VLF sounder for D-region studies. Operating on several fixed frequencies between 10 kc/s and 23 kc/s, they hope to obtain reflection coefficients and also, by means of spaced receiver measurements, to determine the drift direction and velocity of D-region inhomogeneities.

Of particular importance during the last three or four years has been the initiation of a program of rocket exploration of the D region. Rocket experiments designed to investigate the lower ionosphere have been reported by Kane (1959, 1962, 1963), Heikkila (1962), Yonezawa (1962), Bowhill (1962), Mechtly (1962), Jespersen et al. (1963), Smith (1963) and Hall (1963). The majority of the D-region rocket experiments reported to date involve the reception in the rocket of CW radio signals transmitted from the ground. Frequencies from 202 kc/s (Hall 1963) up to and including 2.5 Mc/s (Jespersen et al. 1963) have been used for this purpose. Typically, both amplitude and phase measurements are made at several frequencies as the rocket progresses through the lower ionosphere. The Scandinavian group has shown that by alternately transmitting waves of ordinary and extraordinary polarization and comparing the observed differential absorption with the difference in absorption of the ordinary component of a relatively low frequency (2.5 Mc/s) and a relatively high frequency (22.5 Mc/s), both electron density and collision frequency can be obtained.

Several types of direct (in situ) measurements have also been employed in D-region rocket experiments. Smith (1961) has reported a rocket observation of positive ion conductivity between about 50 and 90 km from which positive ion density can be deduced. Also, Smith (1963a) has suggested that the Langmuir probe technique, which he has used to good advantage in many E-region experiments, may actually be capable of producing useful D-region information as well. Japanese workers have developed an RF resonance probe that has been used to measure positive ion densities in the upper D, E, and F regions (Yonezawa 1962). Such D-region rocket results as were available at the time of preparation of this survey have been included in the summary that follows.

The illustrations presented below, represent an attempt to summarize the principal features of our present knowledge of the height distribution of electrons in the D region. For the purposes of this survey, the D region is taken as that portion of the ionosphere lying below about 90 km. It will be seen from some of the results given below, that ultimately as the observational facts become clearer, it might become necessary to divide the D region into two parts; an upper region between 65 and 85 km and a lower region between 50 and 65 km. The designation "C region" has been suggested for the lower region.*

The ground-based experiments described above have provided the majority of the data going into the summary illustrations. Clearly, these experiments would be expected to furnish the best synoptic information on diurnal and seasonal variations in the gross structure of the D region. Also, unpredictable natural disturbances such as sudden ionosphere disturbances (SID), and polar cap absorption events (PCA), are best studied by a program of continuing systematic observations. In contrast, rocket experiments are capable of provid-

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*The term "C region" was first used by Friend and Colwell (1937) to apply to a portion of the troposphere between 1 and 12 km from which they had obtained high frequency radio reflections.

ing information on the detailed height profile of electron density, though only at isolated times and places.

Figure 1a shows a number of midday profiles of electron density in the D region determined using the cross modulation experiment (dash and two dots), the partial reflections experiment (dotted curve), and rocket experiments (continuous and broken curves). As far as possible, the data have been selected to represent normal midday conditions at an intermediate level in the solar activity cycle. According to Smith, the portion of curve 5 below 90 km should be considered questionable because the behavior of the Langmuir probe at these altitudes is not yet understood. The thin dashed curve shown on the figure is an attempt to derive a smoothed midday profile based on the six individual electron distributions. The basic difference between the D-region profiles shown here and those summarized in 1960 by Ratcliffe and Weekes (1960) is that the present profiles contain between 5 and 10 times more ionization in the 50 to 65 km height range. Midday E-region maximum electron densities for periods of sunspot minimum and sunspot maximum as observed with ionospheric vertical sounders are also shown in Figure 1a. To the extent that the same solar radiations responsible for producing E-region ionization also affect the upper portion of the D region, a similar sort of solar cycle variation would be expected in the D-region profile. Titheridge (1962a) estimates a four-fold increase in D-layer electron densities from sunspot minimum to sunspot maximum.

Figure 1b shows the few nighttime D-region rocket profiles that are available. At night the D region essentially disappears, leaving behind an E region whose maximum electron density is reduced by nearly two orders of magnitude. The exact shape of the profile at heights below about 90 km and densities less than 100 electrons/cm^3 is poorly known.

Figure 2a illustrates the diurnal variation of the electron density profile in the D region. The curves shown are necessarily based exclusively on the cross modulation results reported by Barrington et al. (1963). Because the cross modulation experiment is not particularly sensitive to the detailed shape of the electron density profile, these results should be taken as representative of the diurnal changes in average behavior of the gross structure of the D region. Such data as are available on the seasonal variations in the D-region electron density profile are shown in Figure 2b. Here the results obtained by Belrose (1963a) using partial reflections are compared with the cross modulation results of Barrington et al. (1963). Except for the tendency for greater electron densities during the summer period, the two sets of profiles are considerably different. A note of caution needs to be injected here, however. In deriving these results, in both experiments it was assumed that any seasonal variation in electron collision frequency could be neglected. If indeed, as three rocket experiments suggest, (Lagow et al. 1960, Kane 1962, Jespersen et al. 1963), such a seasonal variation in collision frequency does exist, then the apparent seasonal changes in D-region profile suggested here might be entirely fictitious. Obviously, additional observations pertaining to diurnal and seasonal variations in the D-region electron density and collision frequency are sorely needed.

From time to time, depending on the activity of the sun, the location of the observing station, and other factors probably meteorological in nature, major perturbations take place to the normal height distribution of electrons in the D region. An important class of perturbations are associated with three types of solar-terrestrial phenomena:

1. large enhancements of X-ray emission from the sun at times of solar flares (SID),
2. emission of energetic protons from certain large solar flares (PCA), and
3. injection of corpuscular radiation into the earth's upper atmosphere, particularly within the auroral zone, during times of magnetic and ionospheric storms.

A fourth type of perturbation, even more frequent than the first three, is connected with the periods of anomolously high absorption that are observed frequently during the winter months at temperate latitudes. Electron density profiles representative of each of these four types of disturbances are shown in Figures 3 and 4.

Figure 3a shows the smoothed midday D-region profile from Figure 1a along with the D-region profile observed by Belrose and Cetiner (1962) during a solar flare of importance 2+. Also shown is a theoretical D-region profile for a moderate solar flare derived by Nicolet and Aikin (1960). Gardner (1959) and Titheridge (1962), on the basis of partial reflections studies, concluded that average solar flare disturbances (SID) represent an increase of from 500 to 1000 electrons/cm^3 in the 60 to 75 km height range with lesser increases at higher altitudes.

D-region profiles during three typical polar cap absorption events (PCA) using three different observing techniques are shown in Figure 3b. (Again the normal midday curve is shown for comparison.) Curve 1 was obtained from the partial reflections experiment (Belrose 1963a), curve 2 during a rocket experiment (Jackson and Kane 1959), and curve 3 from the multi-frequency riometer experiment (Parthasarathy et al. 1963). All three profiles were obtained during polar cap absorption events in which the cosmic noise absorption on 30 Mc/s was between 2 and 3 db. The 3 profiles are in remarkably good agreement over the height range between 50 and 85 km lending some confidence to the validity of the observations. It can be seen that D-region electron densities below about 70 km are increased by about a factor of 20 during PCA events of this magnitude.

Profiles representative of conditions in the D region during auroral disturbances are shown in Figure 4a. The profiles include three rocket profiles obtained during periods of auroral absorption by the Scandinavian group (Jespersen et al. 1963) as well as average profiles obtained by Holt et al. (1962 and 1963) employing both the partial reflection and the cross modulation techniques during auroral disturbances at Tromoso, Norway. Note that curve 1 represents the rocket observations taken at a time when the absorption as measured by a 27.5 Mc/s riometer was about 6 db; curve 2, about 1 db; and curve 3, about ½ db. The general agreement between Holt's average curves (4 and 5) based on ground-based observations during a number of auroral absorption events and the rocket results is quite good. The correspondence between a partial reflections profile (curve 6) determined by Holt and the rocket profile obtained within 10 minutes of the same time (curve 1) is very satisfying and lends confidence to the partial reflections technique.

An example of the variability in winter D-region electron densities at temperate latitudes (the so-called D-region winter anomaly) as observed by Belrose (1963a) using partial reflections is shown in Figure 4b. Although the 3 days shown were all magnetically undisturbed and PCA events were not known to have occurred, D-region electron densities in the 60 to 75 km height range were approximately 5 times greater on February 22 than on February 20. Titheridge's results (1962) suggest, however, that the average D-region electron density increase during an event of the winter anomaly type is more like 80%. The D-region winter anomaly was first detected in ground-based absorption measurements. It was observed that during the winter at latitudes between about 30° and 60° many days exhibit much higher absorption than would be expected if the amount of absorption depended primarily on the cosine of the sun's zenith angle. Another puzzling feature is the apparent localization of the region of enhanced D-region electron densities. Absorption measurements suggest that the distance over which the enhancement takes place is typically several thousand kilometers (Dieminger 1962). It would seem, therefore, that the explanation of the D-region anomaly may likely involve meteorological effects of one type or another. That is, relatively local changes in the temperature, composition, or wind structure in the lower atmosphere may be required to account for the observed effects.

Recently Gregory (1961) and Titheridge (1962b) have summarized a large body of data that pertains to the D- and E-region altitudes at which partial reflections tend to occur. Gregory, using 1.75 Mc/s, observed a distinct preference for heights of 55, 61, 66, 74 & 86 km for the bottom edge of daytime D-region stratifications in New Zealand. Titheridge, analyzing two years observations on 0.72 Mc/s in England, found a similar tendency for preferred heights at 71, 80, 90 and 100 km and was able to reconcile his heights with those obtained by Gregory. The existence of similarly favored levels for wind shears (Seddon & Jackson 1958) suggests that the relationship recently postulated between wind shears and sporadic E (Whitehead 1961) may also apply in the D region. As a result of his study, Gregory concluded that the observed partial reflections were due to turbulent scatter in the presence of a gradient of electron concentration. Layzer (1962) has discussed the maintenance of a suitably turbulent scattering layer by wind shears.

Before moving on to the higher regions of the ionosphere, a brief review will be given of the current theories concerning the formation of the normal D region. The first satisfactory theories for the production of the D region were developed by Nicolet (1945) and Houston (1958). The photoionization of NO below 100 km by Lyman α radiation (1216A) was put forward as the process responsible for D-region ionization. As early as 1952, Bracewell and Bain (1952) hypothesized a two-layer D region in order to explain the results of their 16 kc/s propagation studies.

The possibility of a second D region ionization mechanism was first considered by Nicolet in 1958. Shortly thereafter Moler (1960) demonstrated that a quantitatively reasonable two-layer D region could be deduced theoretically assuming ionization of the lower part of the region was by means of cosmic ray primaries and that the free electrons in the upper portion were created as a result of the photoionization of NO by Lyman α. He also showed that a significant diurnal variation was to be expected in the lower D region because of the effects of photodetachment on the cosmic ray-produced ionization and that this diurnal variation could account for several features of VLF propagation that occur around the time of sunrise and sunset. Chapman and Davies (1958) had earlier suggested that a photodetachment mechanism could account for the diurnal constancy of one component of D-region absorption.

Nicolet and Aikin (1960) also undertook a comprehensive theoretical treatment of the formation of the D region and reached the following conclusions. The separation between the E region and the D region occurs near 85 km at the mesopause level. While the lower tail of the E layer is due to ionization by X-rays of 31A or shorter wavelength, the portion of the D region between 65 and 80 km is chiefly the result of the ionization of NO by Lyman α radiation. The part of the D region below 65 km is formed by the ionizing action of primary cosmic rays on O_2 and N_2. Some of the features of the lower ionosphere during various types of solar disturbance come about because markedly different solar radiations are responsible for maintaining adjacent portions of the electron density profile. Nicolet and Aikin also treated the question of the height distribution of negative ions during the day and showed that at heights below about 65 km, the ratio of negative ions to electrons may become significantly greater than 1. Figure 5 shows a comparison between the theoretical D-region electron density profile derived by Nicolet and Aikin for a quiet sun and the smoothed midday D-region profile obtained from Figure 1a. Though there are significant differences in structural detail, the comparison suggests that at least the gross shape of the distribution of electrons in the D region seems to be understood.

A further refinement of the theory described above has been given by Aikin (1962). In this work he analyzed the sunrise effects to be expected in the D region and showed that the combined action of cosmic rays and photodetachment from negative ions leads to a rapid build up of the lower portion of the D region within a short time after layer sunrise. However, solar X-rays and ultraviolet radiation do not penetrate the D region to any great extent at the time of optical sunrise at D-region altitudes (layer sunrise). Consequently, it is only just before ground sunrise that the major portion of the upper D region is produced, thus leading to a time dependent two-layer model for the D region. However, studies of sunrise and sunset effects during PCA's and auroral absorption events suggest that even this picture may be an over simplification (Hultquist 1963, Reid et al. 1963).

Summarizing, it would appear that at least three different ionizing agents play a role in determining the normal D-region electron density profile -- cosmic ray primaries in the lower D region (below 70 km), Lyman α in the mid-D region (70-85 km), and X-rays in the upper D-E region transition (above 85 km). The exact form of the resultant electron density profile depends on balance between the number of electrons produced by these agents and the number of electrons lost by recombination and attachment at each level. While the detailed shape of the distribution of electrons in the D region is not yet well known, the general features of the average profile are beginning to emerge. In order to reconcile certain observational results, it seems necessary to suppose that wind shears or other localized meteorological effects regularly distort the mean profile, producing stratifications of varying thicknesses and intensities. In addition, turbulent strata capable of scattering radio waves must also be frequently produced by the same or similar meteorological effects.

THE NORMAL E REGION AND SPORADIC E

As in the treatment of the D region, recent observations pertaining to the structure of the regular E region and sporadic E will be first reviewed and then current theories of formation will be discussed briefly.

Because of the large volume of conventional vertical soundings data that has been accumulated over the last decade and a half, some features of the E region are well known. In particular, the approximate height range within which the regular E layer is located (90-130 km) and the geographic and temporal variations of the electron density at the peak of the E layer have been readily obtained from ionograms. (At least one worker, however, has questioned the physical meaning of penetration frequency data in view of the complexity often present near the E peak (Robinson 1960). The phenomonology of sporadic E also has been actively pursued using data from the world network of ionosondes. However, several important features of the E region are not well suited to study using conventional vertical incidence data. Specifically, progress has only recently become significant on the problems of the fine structure of the E-region electron density profile, the shape of the profile between the E-layer peak and the base of the F layer, and the electron density structures responsible for sporadic E. Recent advances have come about both because of a growing rocket program involving E-region studies and through the use of improved ground-based sounding techniques.

Three electron density profiles representative of the normal midday E layer are shown in Figure 6a. These profiles resulted from rocket experiments involving two different techniques; the asymmetric Langmuir probe (Smith 1963a) and the Japanese RF resonance probe (Miyazaki et al. 1960; Yonezawa 1962). The strong similarity between the profiles, despite differences in season and observing location, supports the view that the gross shape of the midday E-layer profile is relatively constant. Note that during midday at least, there is little evidence for a valley between the E and F regions. The occurrence of stratifications or irregularities near the E-layer peak seems to be a common feature of the profiles obtained in rocket experiments.

Figure 6b shows three rocket profiles of electron density taken in the nighttime E layer (Smith 1962, 1963b). Also shown on the figure are average midnight values of the maximum electron density in the night E layer for solar maximum and solar minimum observed by Hough (1962) using a low-frequency ionosonde. The only other values of night E-layer maximum electron densities that have been reported, those published by Elling (1961), are in substantial agreement with Hough's data. It is significant that both the rocket experiments and the low frequency ionosondes observe marked stratifications (sporadic E) as the prominent feature of the nighttime distribution of electrons in the E region. In fact, on more than 50% of the nighttime low-frequency ionograms examined by Hough, the regular E-layer penetration frequency was obscured by "blanketing" sporadic-E reflections. It should be noted that the available data suggest that a rather appreciable valley may exist at night between the E and the F layers.

Some results pertaining to the diurnal variation in gross E-region structure are shown in Figure 7. These profiles were obtained by Paul and Wright (1963) employing an analysis technique that makes use of both magnetoionic components observed on a ground-based ionospheric sounding. Although the detailed shape of the profile in the re-entrant portion of the electron distribution cannot be determined (the dashed portion of the profiles are illustrative only), given sufficiently accurate virtual height data, the analysis does give the proper height step between the E-layer peak and the base of the F layer as well as the starting slope at the base of the F layer. These results show that the height at which the E-layer peak is formed decreases as midday is approached and that the width (and perhaps the depth) of the E-F region valley also decreases. Davies and Saha (1962) have also examined the problem of estimating the depth of the E-F region valley from ionograms. Based on a preliminary study, they report valleys as deep as 40% (minimum electron density in valley equals 60% of E-region peak density) during the early morning and as shallow as 20% in the afternoon. However, in view of the fact that none of the daytime E-region rocket experiments reported to date have observed valleys of any appreciable width or depth, the results outlined above should probably be treated with some caution.

Except for the occurrence of stratifications and ledges, including sporadic E, the E layer is relatively immune to disturbance effects. It has long been known, however, that increases of 20% or more in peak E region electron density sometimes occur during solar flares (Taubenheim 1957). Only very minor perturbations to the temperate latitude E layer are observed during ionospheric and magnetic storms. While most E-region anomalies are not large enough to be important in practical radio communication, they are nonetheless of considerable theoretical interest. Appleton and Lyon (1961) have reported the results of a rather complete survey of these effects. Of course, in the auroral zone, under the influence of large corpuscular fluxes during disturbed periods, substantial increases in D- and E-region electron densities are known to take place.

It remains to review the present state of our observational knowledge regarding the distribution of electrons responsible for sporadic E. The term "sporadic E" (or Es) has come to include a variety of phenomena which are manifested on ionospheric soundings as echoes from the E region at frequencies greater than the normal solar-controlled E-layer penetration frequency. We have seen that stratification and irregularities in a weaker or stronger form are a common feature of E-region electron density profiles obtained by rockets. Rocket profiles taken during times when nearby ground sounders are recording sporadic-E echoes almost always exhibit either sharp gradients in the electron density profile or thin strata of enhanced electron density at the appropriate height. However, from ground-based soundings it is known that many different varieties of sporadic E occur, depending on geographic location, time of day, season and other factors. The relatively few rocket results that have been reported to date necessarily refer only to particular times and places. Consequently, our direct knowledge of the ionization structures causing sporadic E is still very fragmentary.

Recently, rocket profiles showing the best evidence of sporadic E have been obtained by Smith using a modified Langmuir probe technique (1962, 1963b). The two profiles in Figure 6b, attributed to Smith, show strong stratifications presumed to be associated with sporadic E. It can be seen that these stratifications represent enhancements of from 2 or 3 to 20 times the background electron density and are generally 2 to 5 km in thickness. The nighttime evidence shown here is not inconsistent with the view that sporadic-E echoes received by ground-based sounders are the result of reflections from over-dense relatively thin strata embedded in the regular E layer. However, Seddon, in a recent summary of older sporadic-E rocket results (1962), states that the earlier data, derived primarily from daytime rocket experiments, indicate that, in the majority of cases, a steep gradient in electron density, rather than a thin over-dense layer, seems to fit the observations best.

Results of a late afternoon rocket firing into sporadic E have recently been given by Smith (1963b). Figure 8 shows the principal features of the electron density profiles obtained on the ascent portion of the flight along with the ionogram obtained at the time of launch. It can be seen that strong sporadic-E echoes were being detected by the ground ionosonde on frequencies up to 5 Mc/s and greater. If the Es returns are to be attributed to over-dense reflections, then electron densities as large as

3×10^5 would have to be present. While the maximum densities observed during the rocket flight were at about the right altitudes to explain the observed sporadic E, they were a factor of three smaller than those needed for over-dense reflections. It should be noted, however, that the observed maximum electron density corresponds to a plasma frequency of about 2.6 Mc/s which is not appreciably different than the frequency at which the Es layer on the ionogram becomes transparent (about 2.3 Mc/s).

Seddon's summary included a tabulation of preferred heights for high E-region electron density gradients as observed in seven rocket experiments. The preferred heights were about 100, 105, 111, 117, and 129 km. He noted that Manring et al. (1961) have reported a tendency for wind shears to occur at 92, 100, 107, 110, and 130 km, providing some observational support for the theory given by Whitehead (1961). It would seem that more study on the question of preferred heights for high gradients (or stratification) in the E region and the relationship between these heights and those found in the D region, would be very valuable. Obviously, there is a great need for additional rocket data on sporadic-E structures, particularly as related to the various types of Es that have been identified from the study of ionograms. For example, rocket observations in the equatorial E region in conjunction with ground observations of equatorial sporadic E would be very useful.

Ground-based experiments have provided some information on the question of Es ionization structures. For example, oblique incidence VHF propagation studies at temperate latitudes suggest that sporadic E occurs in "patches" that are typically hundreds of kilometers in extent. Also, studies of conventional vertical soundings data have shown that three very different kinds of sporadic E exist, depending on geographical location (Smith 1957). In and near the auroral zone*, Es ionization occurs primarily at night, whereas at temperate latitudes, the principal variation is seasonal, Es being most prevalent during the summer months. In a narrow belt about 700 km wide along the magnetic equator, a third variety of Es occurs that is an almost permanent feature of the daytime equatorial E region. Bowles and Cohen (1962), using radio wave scattering at VHF, attributed this type of Es to ionization irregularities lying in the height range between 100 to 107 km. The present position with respect to our understanding of the mechanisms responsible for producing sporadic E will be outlined following a brief review of recent progress in the theory of the regular E region.

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*On the polar cap, well inside the auroral zone, there is less Es than along and just outside the zone, and its diurnal variation is less marked.

Through studies of the variations of its maximum electron density, the regular daytime E layer was found generally to follow an equilibrium α-Chapman law (Ratcliffe 1960). Subsequently, as more precise information on atmospheric composition and solar radiation has become available, the simple theory had to be modified to include several ionizable constituents as well as several ionizing radiations. In a recent paper on the formation of the D and E layers, Nicolet (1962) concludes that the ionization in the E layer is due to:

1. molecular oxygen ionized by X-rays between 100A and 31A, by ultraviolet radiation of Lyman β type, and also by the Lyman continuu, at $\lambda < 910A$;
2. molecular nitrogen ionized by X-rays between 31A and 100A;
3. atomic oxygen ionized by ultraviolet radiation of the Lyman continuum at $\lambda \leq 910A$ and by X-rays.

Also Norton et al. (1962) have recently demonstrated that it was possible to formulate a model atmosphere between 100 and 300 km that was consistent with both rocket observations of the neutral atmosphere and with rocket observations of the height variation of solar flux in many lines of the solar spectrum. They were also able to deduce an acceptable model ionosphere based on these data. As a result of this work, the authors draw the following conclusions about the E region:

1. the peak photoionization rate in the E region for overhead sun is about 4200 ion pairs $cm^{-3}sec^{-1}$ at about 100 km*
2. about 75% of the electrons in the E region at 110 km are derived from N_2^+,
3. about 90% of the electrons in the E region at 100 km are derived from photoionization by solar radiation in the 44-105A band, and
4. the effective recombination coefficient in the E (and F1) region is of the order of $10^{-7}cm^3sec^{-1}$ and decreases with increasing temperature.

Because uncertainty exists in some of the solar fluxes and cross sections used in the Norton analysis, particularly below 260A, and also because the photoionization rate and effective recombination coefficient are a factor of ten or more greater than those previously accepted, the conclusions just given should probably be treated as tentative.

It would seem that the major factors contributing to the formation of the regular E layer are generally understood (see, for example, Bowhill 1961). However, magnitudes of the pertinent photochemical rates are still not well known owing to uncertainties in some of the important ionization cross sections and rate coefficients. In part at least, further progress depends upon improved laboratory measurements of some of these parameters.

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*for sunspot number of about 50

Until quite recently, obtaining a physical understanding of sporadic E has been a double pronged problem. First, one has had to visualize the ionization structure that might be responsible for the type of sporadic-E echoes being studied and secondly, devise a mechanism that would produce the desired ionization configuration. Now that electron density profiles through sporadic E are beginning to become available from rocket experiments, it is no longer necessary to speculate in a completely uninformed way.

Several notable advances have been made recently in our understanding of sporadic E. The first pertains to a possible explanation for much, if not all, temperate latitude sporadic E. Three years ago, Heisler and Whitehead (1960) called attention to a correlation between sporadic E and the horizontal component of the earth's magnetic field. In later papers (1961, 1962), Whitehead showed that a mechanism dependent on a vertical shear in the horizontal wind for the formation of a sporadic E layer could lead to such a correlation. It can be demonstrated that a horizontal wind shear, in the presence of a magnetic field, leads to vertical movement of the ions and electrons and to the formation of thin layers of enhanced ionization. Whitehead showed theoretically that this mechanism can account for a number of features of temperate latitude sporadic E (global distribution, height of occurrence, stratification, and association with F-region travelling disturbances). In a recent rocket experiment where both the electron density profile and horizontal wind shear were measured, an intense sporadic E "layer" was observed at the same altitude as a shear in the E-W component of the wind and a maximum in the N-S component (Smith 1963b).

A second new theoretical contribution concerns the mechanism responsible for producing equatorial sporadic E. Farley (1963) recently developed a theory that involves two-stream plasma instability as the source of the ionization irregularities in the equatorial electrojet. He finds that irregularities should arise spontaneously in regions in which a sufficiently strong current is flowing normal to the magnetic field lines. The various predictions of this theory seem to be in agreement with some of the observed characteristics of the field-aligned irregularities believed to be associated with equatorial sporadic E. Farley also suggests that the same mechanism may be active in the polar ionosphere during periods of auroral activity.

Rastogi (1962) has presented some new evidence that is suggestive of a relationship between thunderstorms and sporadic E, a possibility first suggested by Appleton and Ratcliffe in 1930. It is difficult to assess properly the significance of the new result, however, due to limited amount of data presented. Another approach which may ultimately advance our understanding of sporadic E involves the release of various chemicals within the ionosphere. If certain metallic vapors are released in the E region, ionized clouds result which can be observed optically and by radio to provide information on diffusion and recombination rates and on the E-region wind system. It has been suggested (Wright 1963a) that the release of easily ionizable material into an existing stratum of sporadic E may give useful data on the structure and maintaining mechanism of sporadic E.

Clearly, additional direct observations of the nature of the ionization structures responsible for the several varieties of sporadic E are urgently needed. Insofar as possible, crucial supporting experiments, pertaining to wind shears and electric current systems for example, should be conducted coincident with the electron density measurements. There also appears to be a need for better observations of the horizontal extent and drift of sporadic-E ionization. Until the body of physically meaningful data on the nature of the distribution of electrons in sporadic E is substantially increased, testing of theoretical hypotheses concerning formation mechanisms will continue to be difficult.

THE SUB-PEAK F REGION

This section will be restricted to consideration of the distribution of electrons between the E layer and the F-layer peak, the higher portions of the profile being discussed in a companion contribution by J. H. Chapman.

A substantial body of F-region electron density profile data, based on "real height" analyses of ionospheric soundings, became available during and just after the International Geophysical Year.

Prior to the close of the last triennium, therefore, the principal features of the sub-peak F region electron density profile had been delineated. Consequently, in this section greater emphasis will be placed on surveying recent progress made toward improving our understanding of the behavior of the F region and less attention paid to presenting a complete summary of the pertinent observations.

A considerable number of papers have been published since 1960 pertaining directly or indirectly to the behavior of the subpeak F region. These fall generally into the following categories: elaboration of photochemical and transport processes pertinent to the F region; theory of formation of the F1 ledge; discovery and elucidation of solar-controlled density variations in the neutral atmosphere; photoionization heating; interpretation of electron density profile data in terms of temperature and/or composition of the upper atmosphere; studies of F-region fine structure, including spread F; solar flare effects in the F region; profile changes during ionospheric and magnetic storms. Following a brief review of the basic processes influencing the behavior of the F region as they were generally understood at the end of the last triennium, recent contributions in these areas will be summarized.

Ratcliffe (1959) presented an outline theory of the F region which serves well as a point of departure from which to view the more recent work. This theory assumed that the F1 and F2 layers are formed by the same ionizing radiations which give rise to a Chapman-like peak of electron production in the F1 layer. The increase in electron density above this level is then supposed to result from a decrease in the rate at which electrons are lost (Bradbury 1938). The F2 peak of electron density was not easily accounted for in Bradbury's theory; however, Yonezawa (1955) and Ratcliffe et al. (1956) overcame this difficulty by the suggestion that plasma diffusion could be responsible for the formation of the observed maximum.

It was further assumed that most of the F-region ionization is produced by the photoionization of atomic oxygen. The peak rate of production (q) as a function of sunspot number (R) was taken as $q = 250\ (1 + 0.016R)\text{cm}^{-3}\text{sec}^{-1}$. The loss process was assumed to be one involving charge-exchange between O^+ ions and O_2 or N_2 molecules leading to a loss rate (β) at a given height (h) of $\beta = 10^{-4}\exp[(300-h)/50]\text{sec}^{-1}$. The daytime bifurcation into the F1 and F2 layers was taken as the indirect result of the transition from a recombination-like loss process in the E and low F regions to an attachment-like loss process at greater heights.

This outline theory made clear the importance of the ratio of the scale height of the ionizable constituent (hi) to that of the constituent determining the loss rate (Hβ). (In a completely mixed atmosphere Hi/Hβ = 1; if the gases making up the atmosphere are in diffusive equilibrium Hi/Hβ = 1.75 or 2, depending on whether O_2 or N_2 is the constituent determining the loss process.) Ratcliffe showed that the shape of the F-region electron density profile is very much influenced by the magnitude of the ratio, the steeper gradient of electron density occurring for the larger ratio. On the basis of a limited amount of data, it appeared that the results favored a relatively small ratio, suggesting more or less complete mixing up to 300-400 km.

It was pointed out that because small alterations in the amount of mixing can produce such significant changes in the electron distribution and the peak density, this mechanism might account for the winter anomaly in F-layer densities. The F-layer winter anomaly pertains to the fact that in temperate latitudes, the F-layer peak electron density is much greater in winter than in summer. In order for this mechanism to be responsible for the anomaly, the mixing would have to be less complete in winter than in summer. With this brief summary of F-region theory as it was generally understood in 1959, the subsequent work will now be reviewed.

A significant portion of the recent work has centered around attempts at solving the continuity equation of electron density in the F2 layer:

$$\frac{\partial N}{\partial t} = q(h,\chi) - \beta(h)N - \mathrm{Div}\,(N\underline{V})$$

in which the time rate of change of electron density, $\partial N/\partial t$, depends on the production rate, q, which is a function of height and solar zenith angle, χ, the loss rate, β, which is a function of height, and a movement term involving the mean drift velocity of electrons, $\underline{V}$.

Because of mathematical complexity, most of the early workers found it necessary to restrict their considerations to an equilibrium solution of the continuity equation. Near midday this is found to be an adequate approximation, the other terms in the continuity equation being much larger than the $\partial N/\partial t$ term. Rishbeth and Barron (1960) carried out such an equilibrium study with particular emphasis on the factors which govern the F2 peak of electron density. They concluded that the maximum electron density and the height at which it occurs, are such that the magnitudes of the production, loss and diffusion processes are approximately equal. The effects produced by vertical drift depend on the ratio of its magnitude to the product of the scale height of the ionizable constituent and the diffusion rate at the peak.

In a subsequent paper, Rishbeth and Setty (1961) attempted to deduce ionization production rates on the assumption that the rate of change of electron density in the sunrise F layer depends principally on the rate of production. Their results suggested that the peak rate of production increases by a factor of 4.5 as the sunspot number increases from 0 to 220. They also suggest that the seasonal anomaly in daytime F2 layer electron density results from changes of the ratio of the concentrations of atomic oxygen and molecular nitrogen in the F region.

The effects of movements of ionization on the rate of change of electron density in the F region at sunrise were considered by Rishbeth (1961) and Hirsh and Knecht (1962). It was shown in the first paper that plasma diffusion and vertical drift had very little effect on $\partial N/\partial t$ in the sunrise F layer, though both factors affected the level at which the peak was formed. Hirsh and Knecht showed that large gradients in the east-west F-region drift velocity, observed at low latitudes around sunrise, might contribute substantially to the rate of change of electron density.

Time-varying solutions to the F-region continuity equation were developed almost simultaneously by two groups. Gliddon and Kendall (1960), assuming an isothermal atmosphere, obtained a solution of the continuity equation in terms of analytic functions, which were evaluated with a digital computer. Briggs and Rishbeth (1961) designed and constructed an electrical analogue computer to solve the non-equilibrium continuity equation. As a result of these studies, considerable insight was gained into the behavior of the ionosphere under the influence of a diurnally varying rate of production. Similarly, it was possible to calculate solar eclipse and solar flare effects (Ferraro 1962) in the F region. Also, it was possible to see how far a time-varying solution of the continuity equation which included only production, loss and diffusion, could explain the behavior of the F region.

Solar eclipses have been used on several occasions to provide ionospheric data from which production and loss rates could be determined (for example, Gledhill 1959). Most recently, VanZandt et al. (1960) deduced production and loss rates that were about ten times greater than those previously derived by Ratcliffe et al. (1956). Using these rates and an internally consistent model atmosphere and solar ionizing flux, Norton et al. (1962) were able to deduce a model E and F1 layer not unlike the observed layers. Yonezawa et al. (1962) also produced a model F region which was in reasonable agreement with observations.

Hirsh (1959, 1962) considered, in detail, the effects of the height dependent loss processes thought to be active in the F region and showed that many features of the observed profiles, notably the bifurcation of the daytime F region into the F1 and F2 layers, could be accounted for in this manner. Major discrepancies remained, however, between the loss rates predicted by Hirsh's model and those necessary to explain the slow decay of the nighttime F region. Our understanding of F-region behavior unquestionably has been impeded by lack of a full appreciation of the various loss processes possible in the F region. The complexity of these processes was recently described by Nicolet (1962).

Shortly after the first satellites were launched, observations of atmospheric drag revealed the presence of significant fluctuations in upper atmospheric neutral gas densities. The observed diurnal and seasonal changes in density have been related to solar-controlled changes in F region temperature (Jacchia 1960, King-Hele and Walker, 1961). The implications of a diurnal temperature variation in the equatorial F region has been investigated by VanZandt and Norton (1961) and others. Hunt and VanZandt (1961) and Harris and Priester (1962) have calculated the photoionization heating to be expected in the F region and find it in general agreement with the temperatures deduced from the satellite drag data except that Harris and Priester take into account a second "corpuscular" heat source, the existence of which has been suggested by Paetzold (1962) and others. It seems clear that future work must take into account both short and long term temperature variations in the upper atmosphere as well as those associated with changes in solar activity.

Attention has continued to be given to examination of F region electron density profiles obtained from ionosonde data with the objective of improving our understanding of the temperature control of ionospheric structure. Wright (1962b), using a thickness parameter of the F2 peak to determine the neutral atmosphere scale height, demonstrated the existence of seasonal and solar cycle variations which may be caused by temperature changes. He also presents evidence to indicate that the so-called "winter anomaly" in F2 peak electron densities is better termed a summer anomaly and suggests that the anomaly results from seasonal changes in composition related to the degree and duration of photoionization heating. Becker and Stubbe (1962), from a similar investigation of the curvature of the F2 layer peak, deduced a neutral gas temperature variation of about 900°K to 1400°K from sunspot minimum to maximum.

So far in this review, our attention has been confined to height distribution of electrons in the ionosphere. However, for some purposes, obtaining an understanding of the horizontal (latitudinal) structure is equally important. The change in F region structure as a function of magnetic dip is well illustrated in Figure 9 (after Thomas 1962). Profiles are shown for four locations having dip angles from 72°N to 7°N. The effect of inhibited vertical diffusion near the magnetic equator is clearly seen. Other factors such as electrodynamically induced vertical motions may also play a role in elevating the low latitude F layer.

Wright, using ionosonde data, has presented a considerable amount of information on the structure of the ionosphere along the 75°W meridian (1962a, 1963b). Figures 10-12, taken from his work, show the principal features of the height distribution of electrons in the sub-peak F region. Figure 10 illustrates the diurnal changes in F layer structure at a high latitude, temperate and equatorial location. (The dashed portions of the profile above the F2 peak were obtained by employing a Chapman layer extrapolation (Wright 1960)). Figure 11 illustrates the seasonal change in F-layer structure at noon at the three locations (note that Huancayo is in the southern hemisphere). Solar cycle effects on electron density profiles observed at Belvoir, Virginia are shown in Figure 12 (Wright 1962b). The profiles, obtained from ground-based ionosonde data, have been extrapolated by Wright to an altitude of 1000 km using as a basis for the extrapolation the observed scale height at the peak of the F2 layer.

Progress has also been made in several other areas pertaining to the F region. Theoretical work concerning the horizontal structure of the equatorial ionosphere has been reported recently by Goldberg and Schmerling (1963) and Rishbeth et al. (1963). These papers attempt to deal quantitatively with the problem of horizontal diffusion of ionization at low magnetic latitudes. The studies of Calvert and Cohen (1961), Cohen and Bowles (1961), Pitteway and Cohen (1961) and others, have done much to improve our understanding of some of the mechanisms responsible for low latitude spread F. Statistical studies of world-wide spread F by Shimazaki (1959) and Singleton (1960, 1962) have also proved very valuable in clarifying the pertinent geographical and temporal variations as did Pendorff's analysis of arctic spread F (1962).

The results of a preliminary study of magnetic storm effects on electron density profile data have been given by Matsushita (1962). However, much more analysis of this type needs to be done before a clear picture of the magnetic storm effects on the F-region electron distribution emerge. Also, the problem of solar flare photon effects in the F region has been under study. Several workers have reported F-region ionization increases at the times of large solar flares (Knecht and Davies 1961; Davies 1962).

In summary, considerable progress has been made since 1960 toward improving our understanding of the behavior of the F region, though certain large gaps remain. In several instances these gaps are related to deficiencies in our knowledge of the neutral atmosphere. For example, the height of the turbopause is not known and doubts concerning neutral and ion composition still exist in the F region. Also, intolerably large uncertainties are present in some crucial reaction rates, calling in some cases for better laboratory measurements. Photoionization rates, especially as a function of solar cycle, are not well enough known and the pertinent loss processes in the F region and their diurnal variability need to be better studied. The precise role played by electrodynamically induced vertical drifts, conjugate transport (Rothwell 1962) and related mechanisms, is still very much open to question. The cause of the winter (or summer) anomaly in F2-layer peak electron densities cannot yet be considered to be known, though several suggestions as to possible mechanisms have been made. Finally, the phenomenon of the ionospheric storm remains a major unsolved problem in ionospheric physics.

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FIGURE CAPTIONS

Figure 1 Normal D-region electron density profiles. (a) Typical midday profiles (1 = Belrose (1963); 2 = Barrington et al. (1963); 3 = Yonezawa (1962); 4 = Adey and Heikkila (Belrose 1963); 5 = Smith (1963); 6 = Hall (1963)). (b) Typical nighttime profiles (1 = Smith (1962); 2 = Smith (1963b); 3 = Smith (1963b)).

Figure 2 Diurnal and seasonal variations in D-region electron density profile. (a) Diurnal variation (after Barrington et al. (1963)). (b) Seasonal variation (dotted curves - Belrose (1963); dashed curves - Barrington et al. (1963)).

Figure 3 D-region electron density profiles during solar flares (SID) and polar cap absorption events (PCA). (a) Calculated and observed profiles for moderate solar flares (see text). (b) Observed profiles during PCA events (see text).

Figure 4 D-region electron density profiles during auroral disturbances and during periods of high absorption associated with the "winter anomaly". (a) Auroral disturbance profiles (see text). (b) Profiles during "winter anomaly" (after Belrose (1963)).

Figure 5 Comparison of theoretical noon profile of D-region electron density derived by Nicolet and Aiken (1960) and smoothed midday profile generally representative of the observations given in Figure 1a.

Figure 6	Midday and night profiles of electron density in the E region. (a) Midday E-region profiles (1 = Smith (after Bourdeau (1963)); 2 = Smith (1963a); 3 = Yonezawa (1962)). (b) Night E-region profiles (1 = Smith (1963b); 2 = Smith (1962); 3 = Smith (1962)).
Figure 7	Diurnal variation in E-and lower F-region structure (after Paul and Wright (1963)).
Figure 8	Rocket profile through "sporadic-E" ionization. Wallops Island, Virginia; 1700 75°W time December 5, 1962, (Smith (1963b)). Ionogram taken at Wallops Island at the time of firing is also shown.
Figure 9	Effect of magnetic dip on the electron density profile in the F region (after Thomas (1962)).
Figure 10	Diurnal variation in the F-region electron density profile at high temperate, low temperate, and equatorial locations.
Figure 11	Seasonal variation in the F-region electron density profile.
Figure 12	Solar cycle variation in the F-region electron density profile at Belvoir, Virginia (after Wright 1962b).

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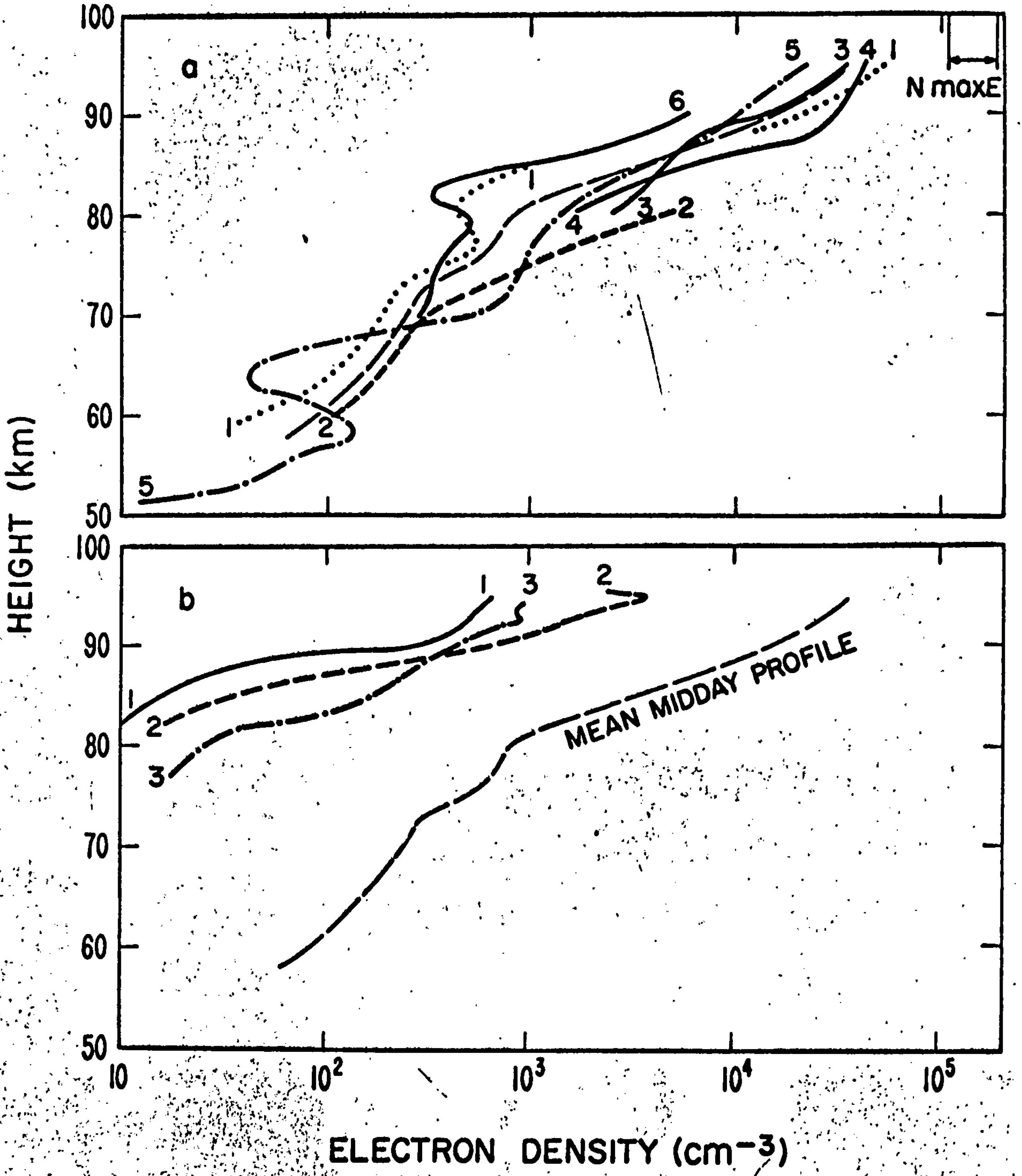
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MEAN MIDDAY PROFILE

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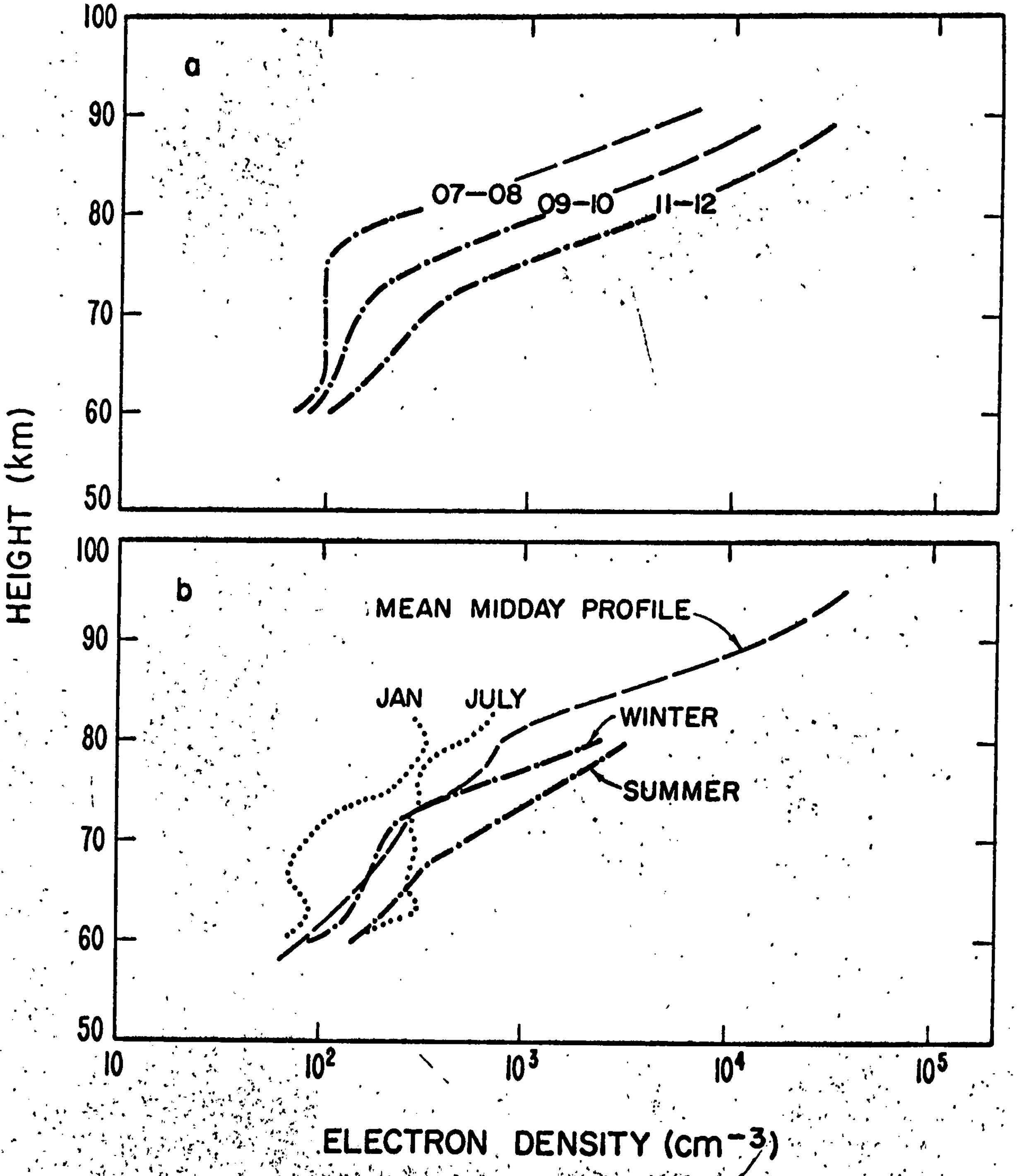
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MEAN MIDDAY PROFILE
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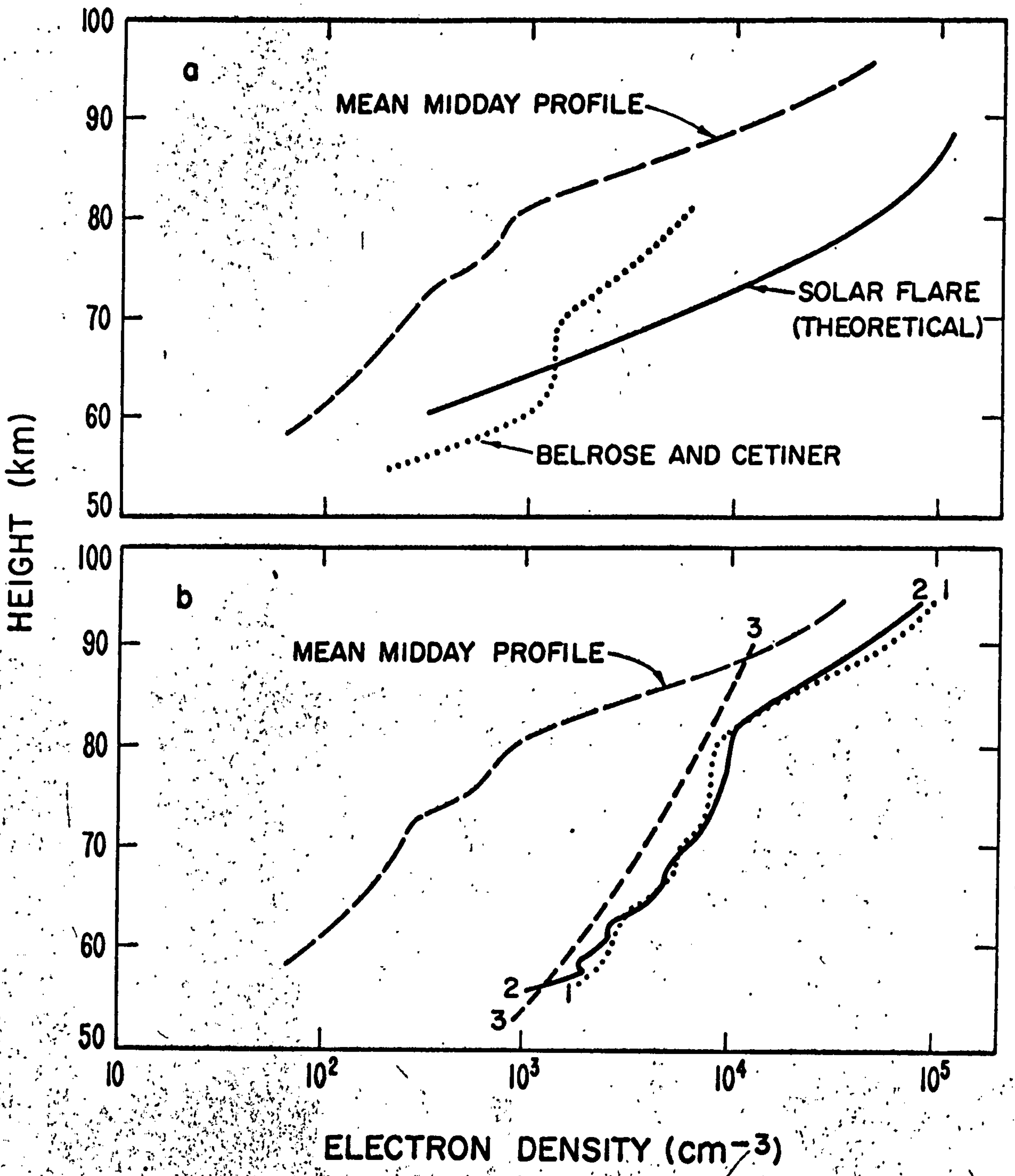
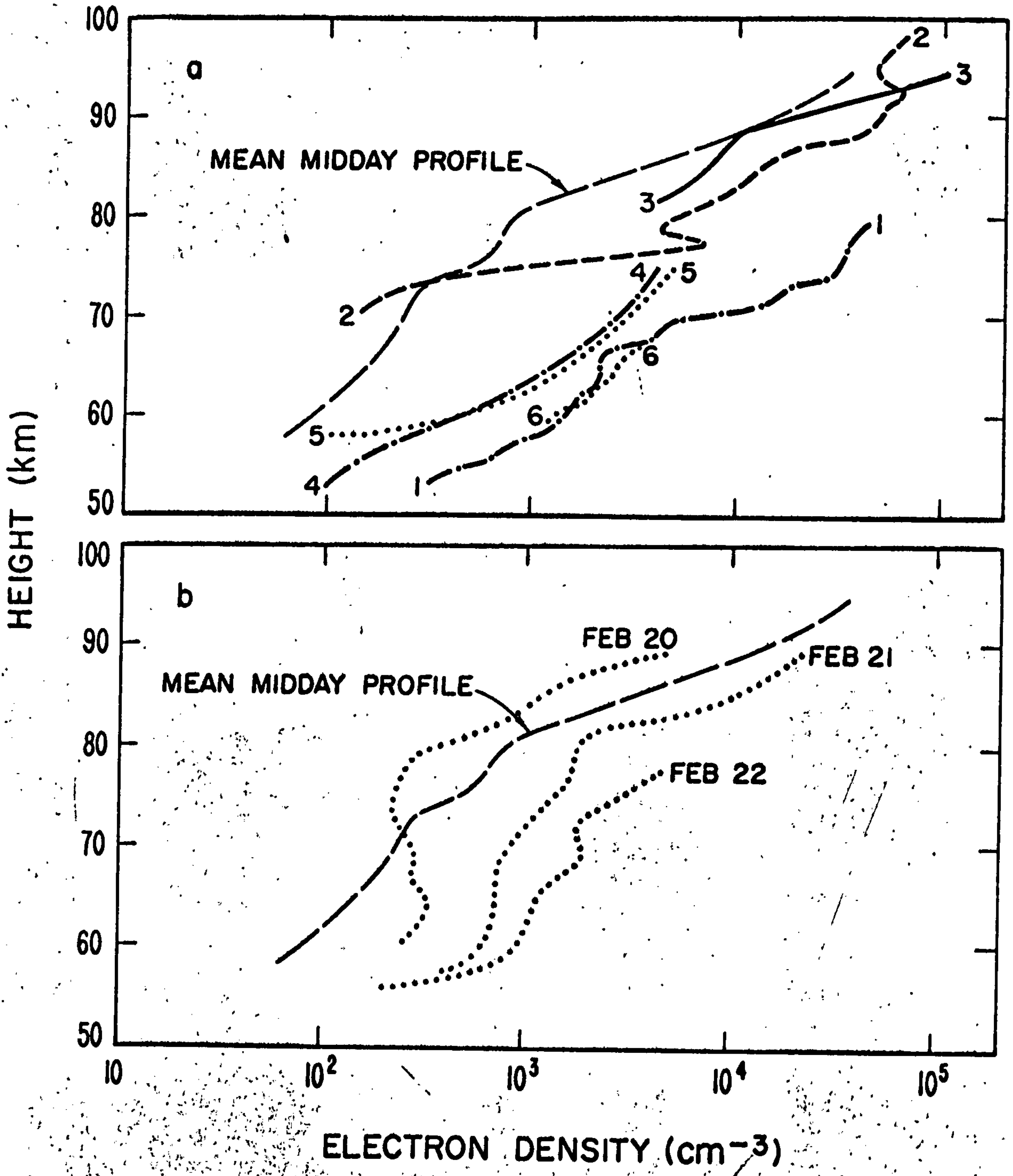
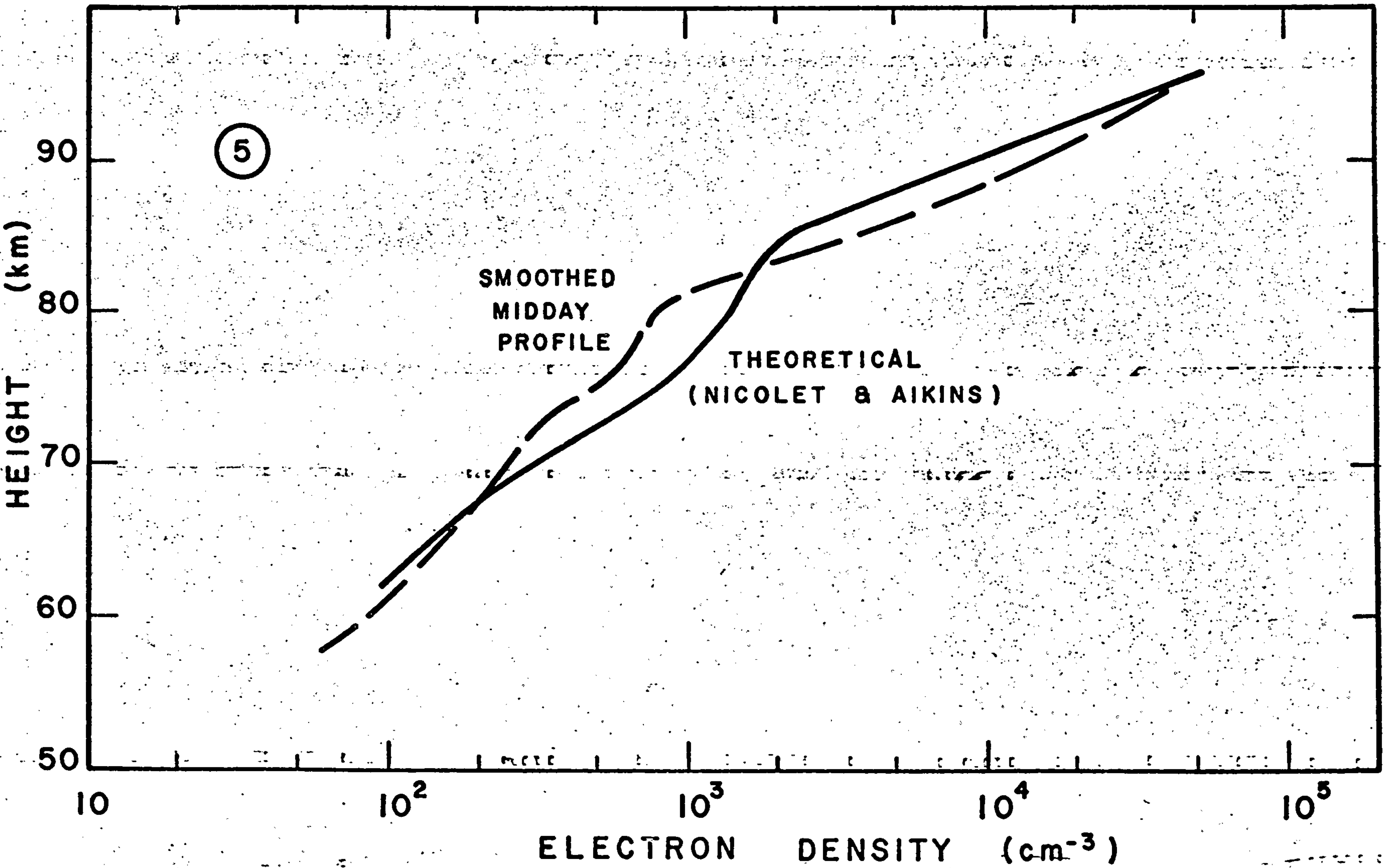
10^5
ELECTRON DENSITY (cm^{-3})


a
MEAN MIDDAY PROFILE
SOLAR FLARE (THEORETICAL)
BELROSE AND CETINER
b
MEAN MIDDAY PROFILE
1
2
3
HEIGHT (km)
100
90
80
70
60
50
10
10^2
10^3
10^4
10^5
ELECTRON DENSITY (cm^{-3})

B-41368

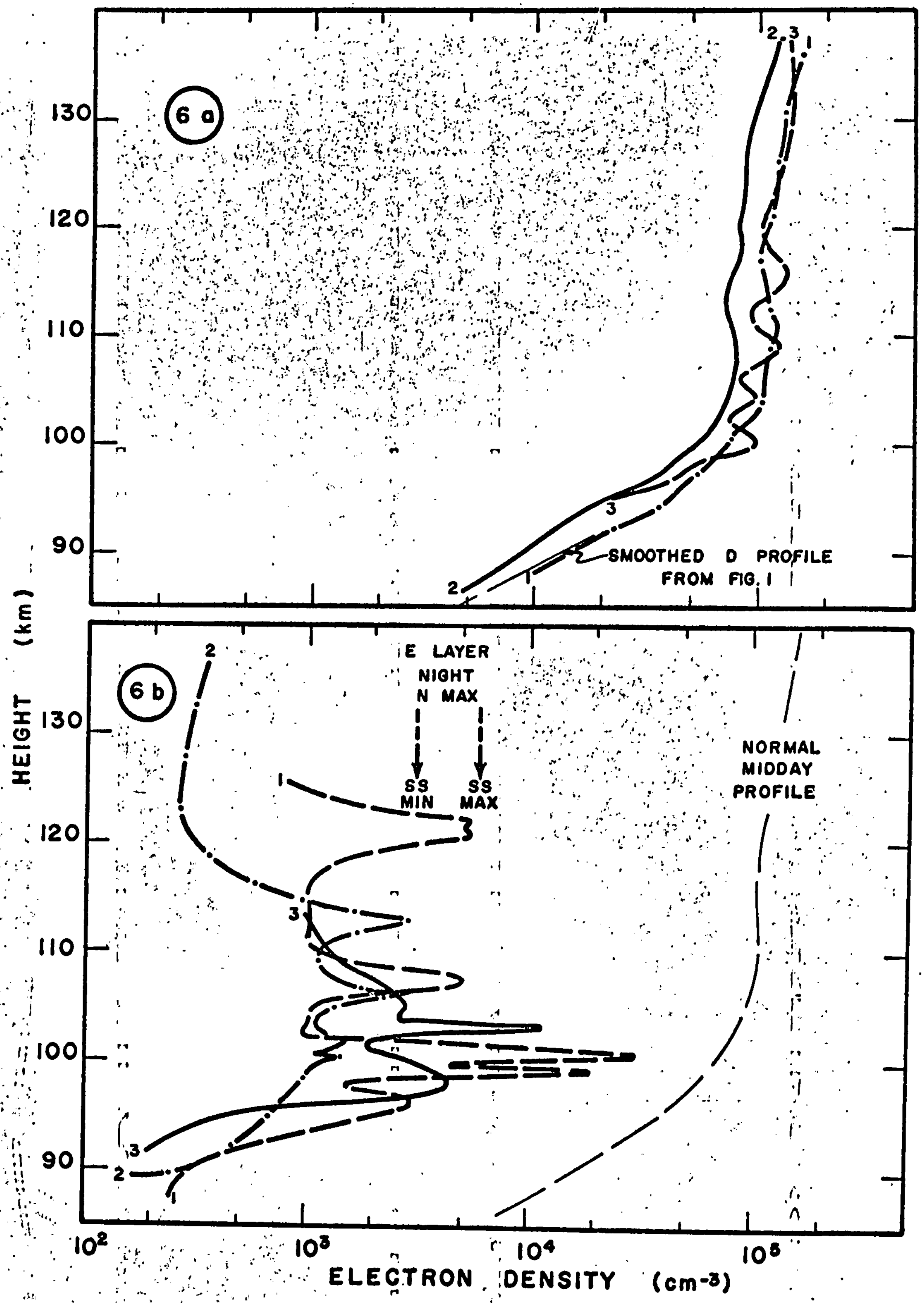

a
MEAN MIDDAY PROFILE
1
2
3
4
5
6
b
MEAN MIDDAY PROFILE
FEB 20
FEB 21
FEB 22
HEIGHT (km)
100
90
80
70
60
50
10
10^2
10^3
10^4
10^5
ELECTRON DENSITY (cm^{-3})

B-41347

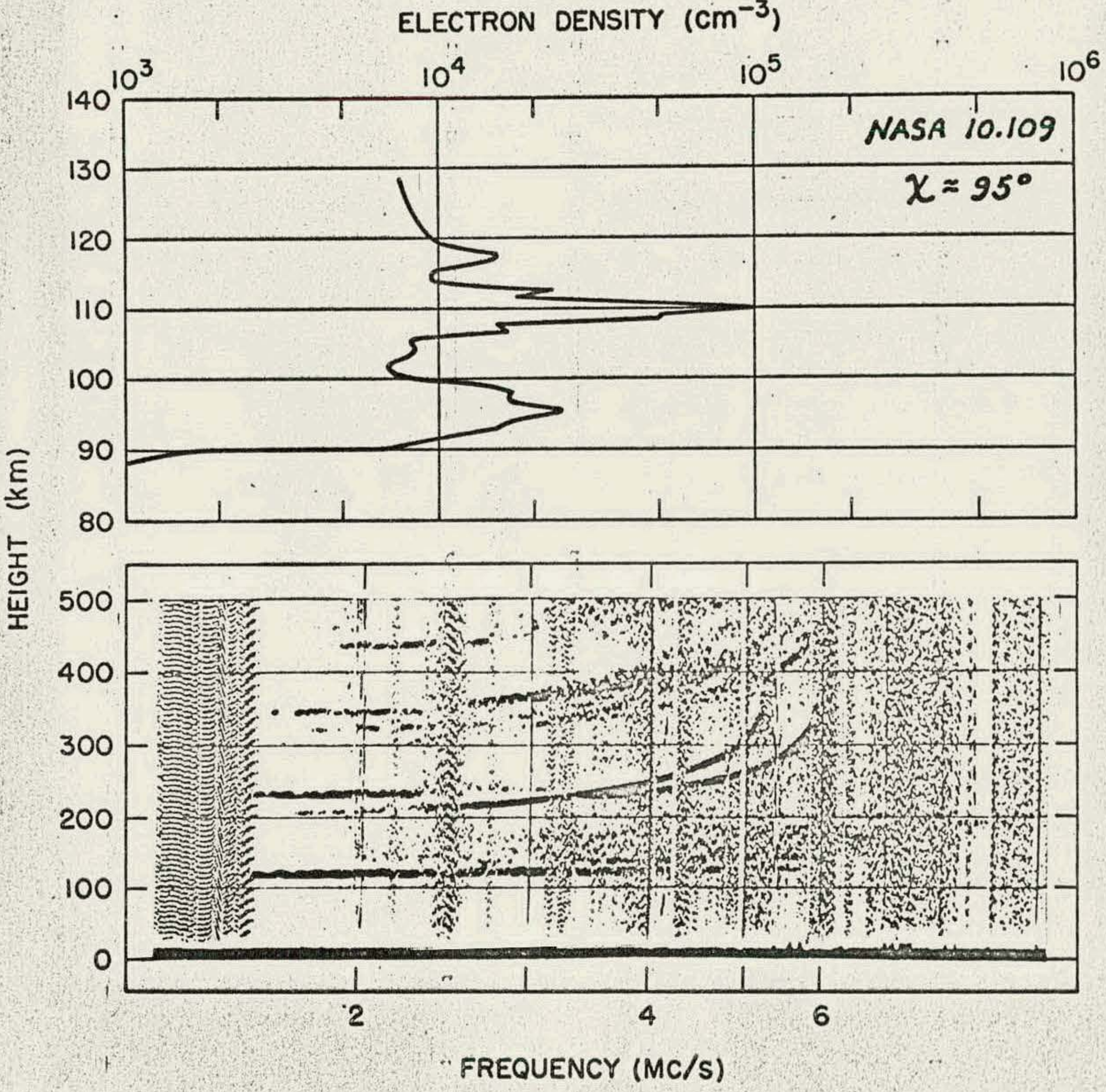


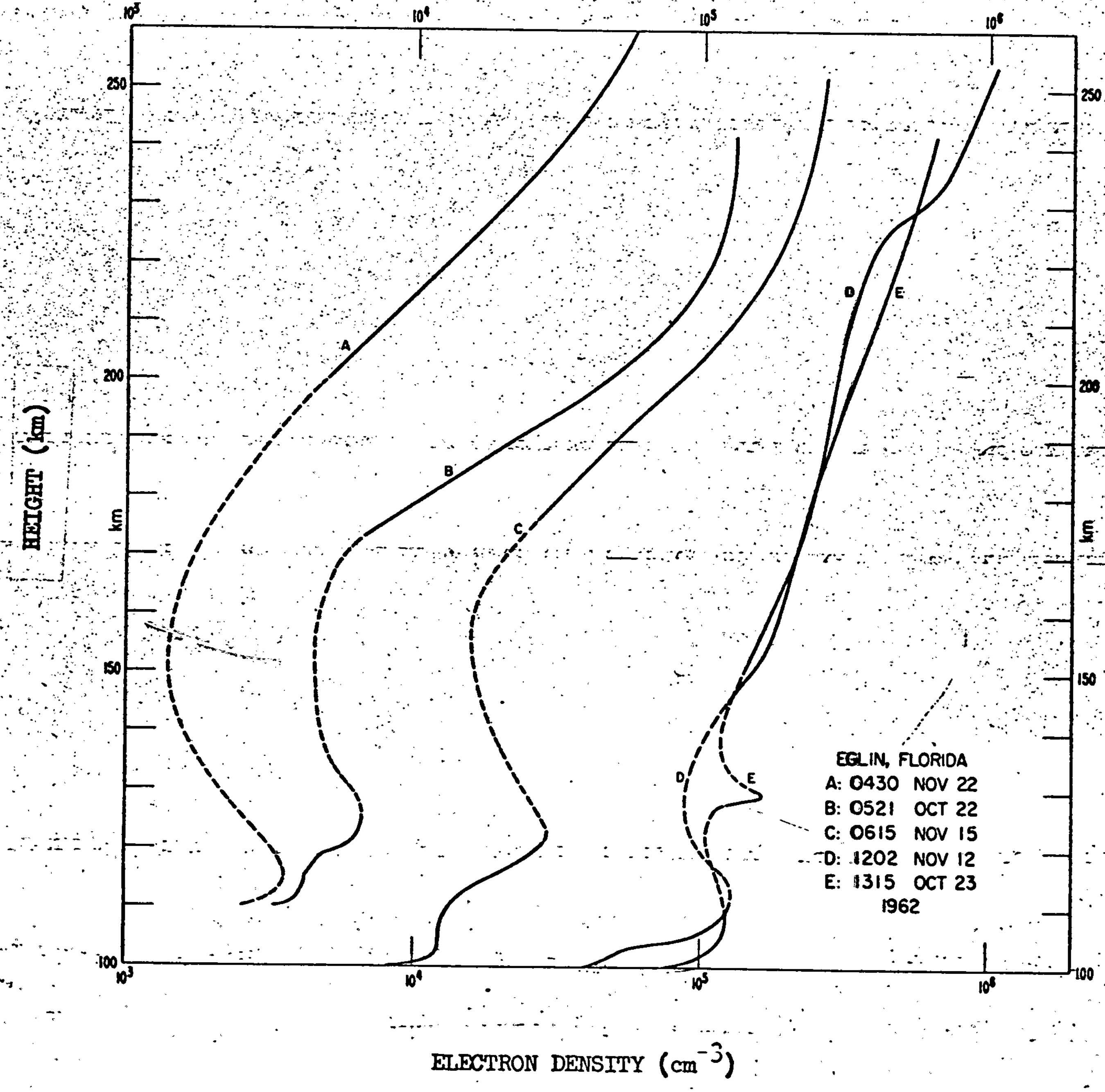
5
90
80
70
60
50
HEIGHT (km)
SMOOTHED MIDDAY PROFILE
THEORETICAL (NICOLET & AIKINS)
10
10^2
10^3
10^4
10^5
ELECTRON DENSITY (cm^{-3})

B- 41017


6 a
6 b
HEIGHT (km)
130
120
110
100
90
2
3
1
SMOOTHED D PROFILE FROM FIG. 1
E LAYER NIGHT N MAX
SS MIN
SS MAX
NORMAL MIDDAY PROFILE
10²
10³
10⁴
10⁵
ELECTRON DENSITY (cm⁻³)

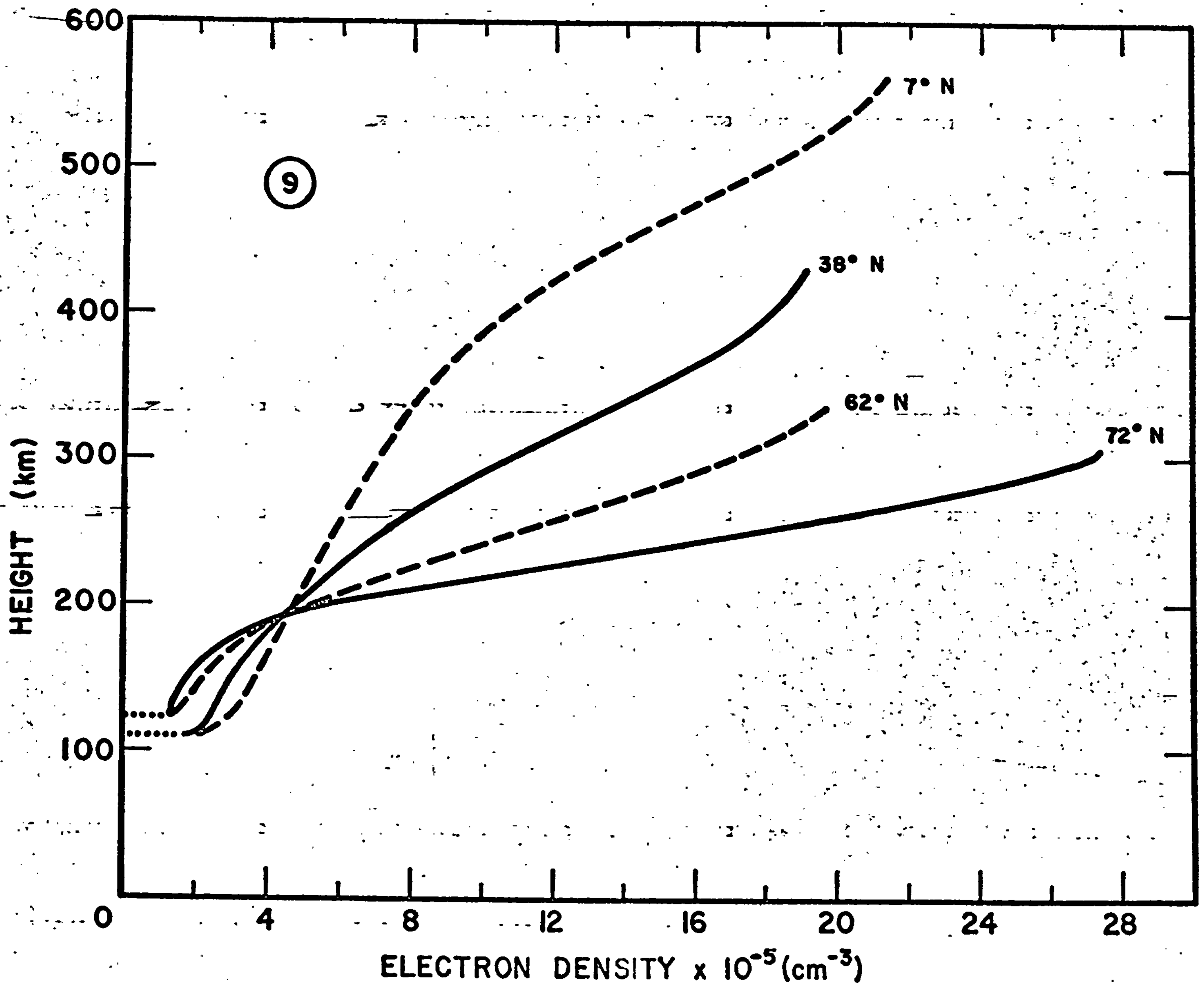
B-41034


ELECTRON DENSITY (cm^{-3})
10^3
10^4
10^5
10^6
NASA 10.109
$\chi \approx 95°$
140
130
120
110
100
90
80
HEIGHT (km)
500
400
300
200
100
0
2
4
6
FREQUENCY (MC/s)

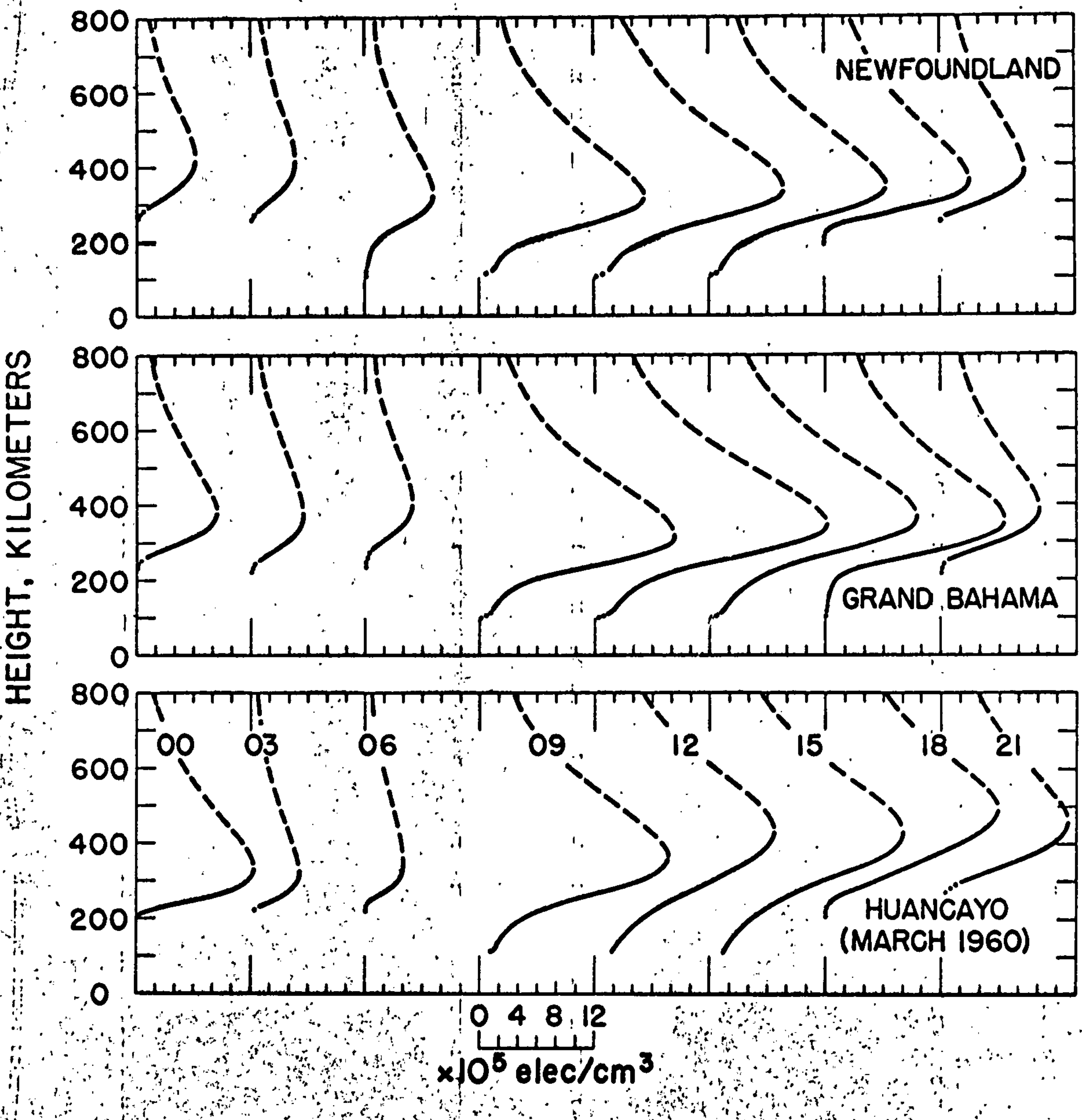


10³
10⁴
10⁵
10⁶
250
200
150
100
km
HEIGHT (km)
A
B
C
D
E
EGLIN, FLORIDA
A: 0430 NOV 22
B: 0521 OCT 22
C: 0615 NOV 15
D: 1202 NOV 12
E: 1315 OCT 23
1962
ELECTRON DENSITY (cm⁻³)

B- 38745


⑨
600
500
400
300
200
100
0
HEIGHT (km)
4
8
12
16
20
24
28
ELECTRON DENSITY x 10^{-5} (cm^{-3})
7° N
38° N
62° N
72° N

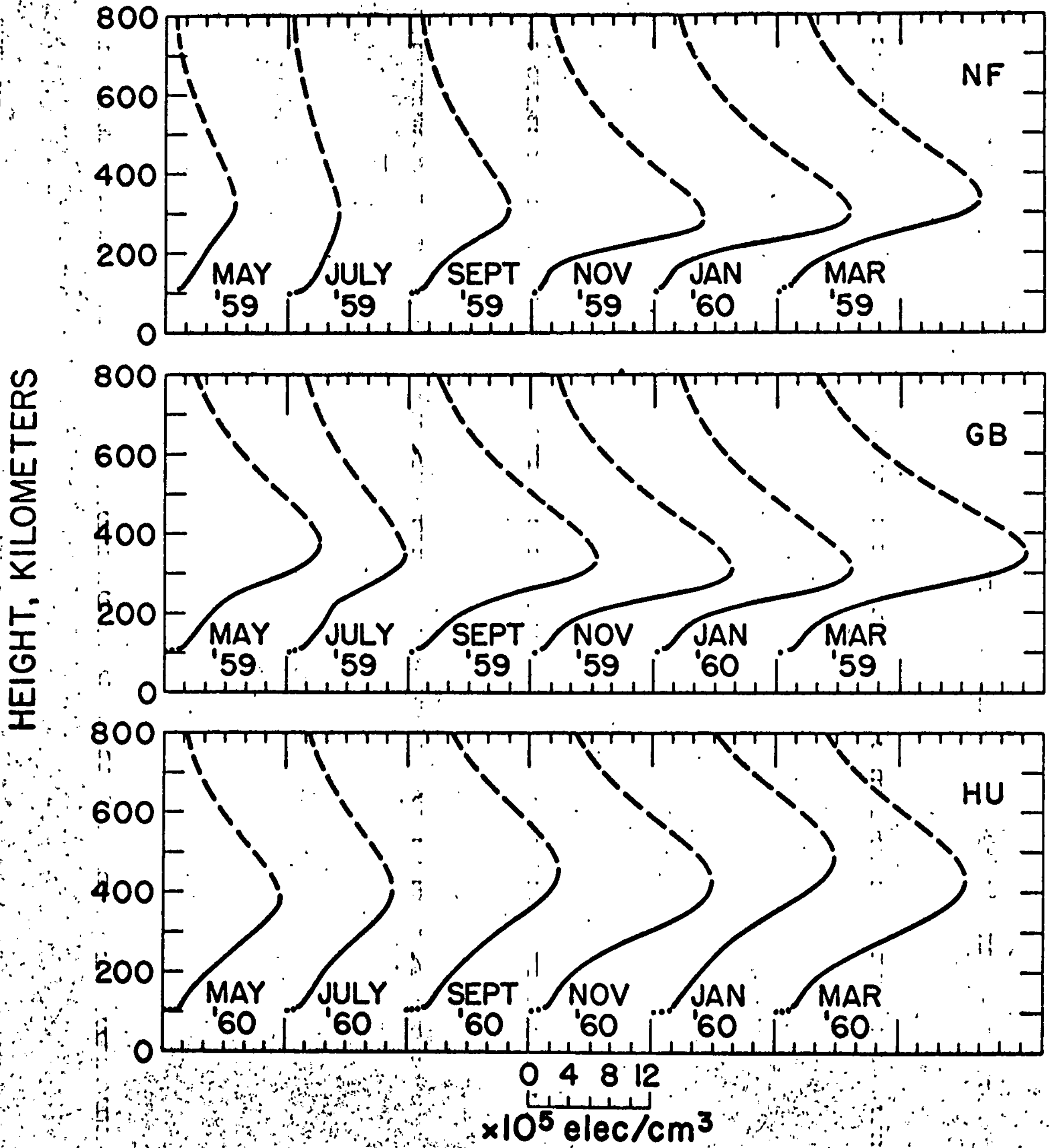
B-41021



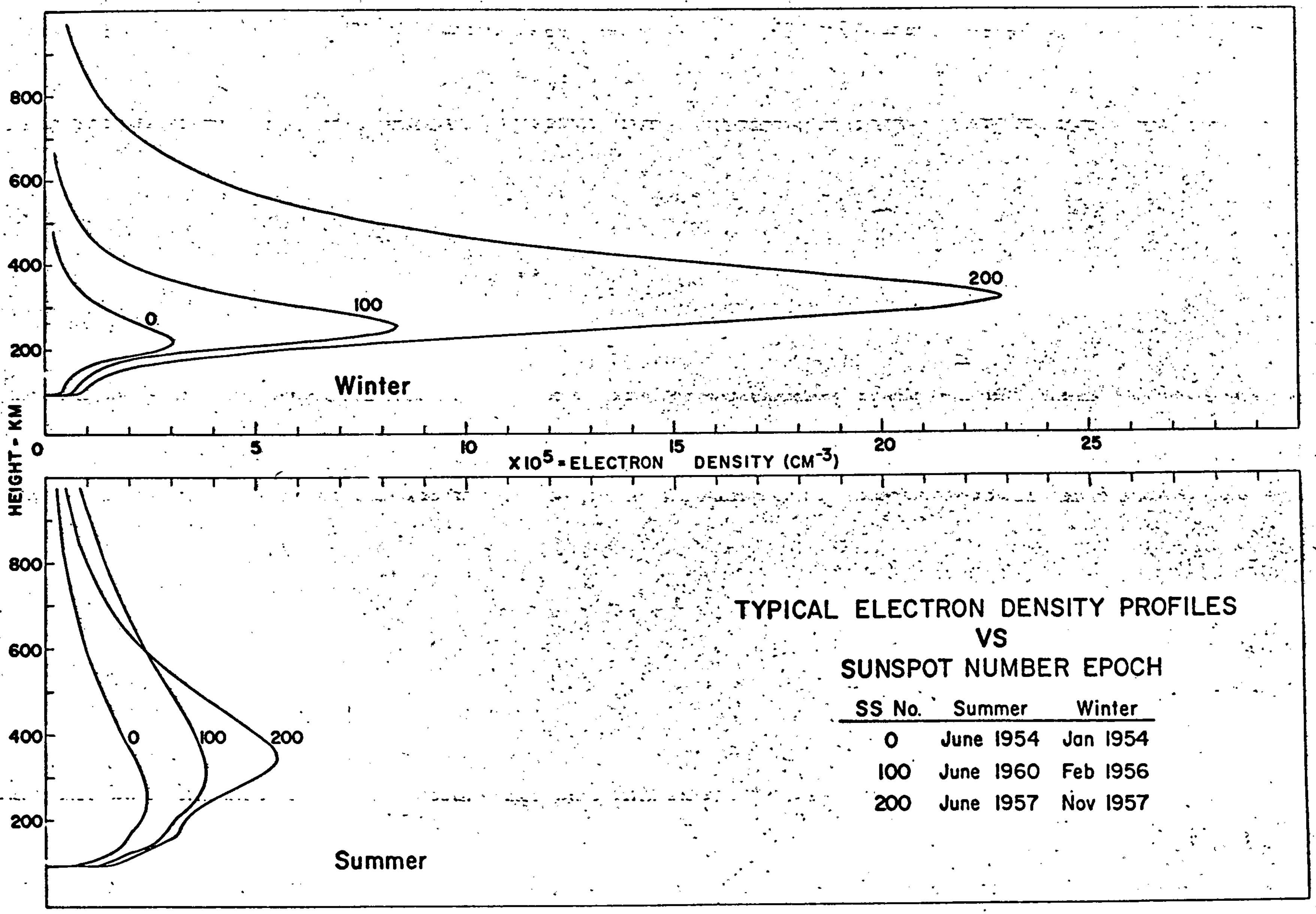
AVERAGE QUIET-DAY PROFILES MARCH 1959

B- 34128

NOON MEAN N(h) PROFILES



B- 34127



TYPICAL ELECTRON DENSITY PROFILES VS SUNSPOT NUMBER EPOCH

SS No.	Summer	Winter
0	June 1954	Jan 1954
100	June 1960	Feb 1956
200	June 1957	Nov 1957