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PROPERTIES OF THE SPORADIC E LAYER AT SODANKYLÄ

TAUNO TURUNEN

Sodankylä Geophysical Observatory
Sodankylä, Finland

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Sodankylä, April 1977 Tauno Turunen

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The present thesis consists of the following seven articles

I Tauno Turunen and M. Mukunda Rao: Sequential Es at Sodankylä, Geophysica 13, 175 (1975)

II Tauno Turunen and M. Mukunda Rao: Geophysical variations at Sodankylä during a geomagnetic storm 17-18 December 1971, Geophysica 13, 183 (1975)

III Tauno Turunen: Measuring the echo amplitudes of Sporadic E layer in swept frequency ionospheric sounding, Geophysica 13, 167 (1975)

IV Tauno Turunen and M. Mukunda Rao: Statistical behaviour of Sporadic E at Sodankylä 1958-19[illegible]1, Geophysica 14, 77 (1976)

V Tauno Turunen: The diurnal variation of Es layer parameters at Sodankylä in summer 1973 based on ionospheric soundings utilizing low fixed gain, Geophysica 14, 55 (1976)

VI Tauno Turunen: The long term variation of Es layer parameters at Sodankylä 1958-1972, Geophysica 14, 61 (1976)

VII Tauno Turunen: Sporadic E layer and magnetic activity at Sodankylä Geophysica 14, 47 (1976)

CONTENTS

1. SUMMARY

In the papers included in the present thesis, properties of the Sporadic E (Es) layer are investigated by using ionospheric data from Sodankylä Geophysical Observatory (geom. lat 63.8^{0}, geom. long. 120.0^{0}). In some cases special experiments were arranged to get information not obtainable from the standard data. Sodankylä station may be in or out of the auroral oval depending on the time of day and the level of magnetic activity. The equatorward boundary of the auroral oval is often near the station. It has been found that three different types of Es activity occur at Sodankylä.

1) Midlatitude types of Es are seen mostly in summer time and appear in two waves the first commencing in the morning at 0800 hours and the second in the evening at about 1700 hours local time. Waves especially appear in the height of Es layers. Events related to the evening wave are usually stronger than events related to the morning wave. The driving force is the semidiurnal component of the atmospheric tidal wave.

2) Auroral zone types of Es layers occur throughout the year in the evening and night time. This part of Es activity is closely correlated with auroral substorms. The ionization in those layers is caused by soft (1 - 10 keV) precipitating electrons, but the details of the Es formation are not well known.

3) Weak diffuse echoes from the lower boundary of E layer can be seen in ionograms under low noise conditions practically always when measuring at very high gain level. This layer can totally dominate the Es parameters in the standard data, although this layer should not be considered as an Es layer.

Long term variations of Es parameters show no clear relationship to the sunspot cycle except in the case of retardation Es . The midlatitude types of Es especially show a peculiar long term variation.

Amplitude measurements indicate that both the critical and blanketing frequencies can be gain dependent at Sodankylä.

2. INTRODUCTION

Narrow ionization enhancements are occasionally formed in the ionosphere at the altitude of 100-150 km in the E-layer. They are called "Sporadic E layers" and their basic properties as deduced from classical ionospheric sounding can be summarized as follows.

1) They appear sporadically and have a life time from some minutes to hours. The occurrence exhibits, however, statistically certain diurnal and seasonal variations. These variations are different for different Es phenomena.

2) Most Es layers form, in ionograms, an echo pattern which has constant virtual height over a wide frequency range. Exceptions are retardation Es, which has group retardation near the critical frequency and slant Es, which has rising virtual height along with increasing frequency. Two of the Es phenomena, auroral Es and equatorial Es, often form a cloud of echoes in ionograms. The latter is not seen at Sodankylä.

3) Frequently there exists a frequency range where the layer is apparently semitransparent.

Well known overall properties of Es layers are summarized by THOMAS and SMITH [20].

Es phenomena are classified into several "Es types", which are fully described by PIGGOTT and RAWER [14]. This classification is presented in paper IV in this thesis.

Midlatitude Es layers are thin, horizontal ionization enhancements in the E layer. Their thickness is from some hundred meters to some kilometers and they are formed because of accumulation of metallic ions around windshear regions as shown by several rocket experiments [3, 5, 6, 18, 19]. The formation mechanism is studied theoretically in several papers, for example by WHITEHEAD [22, 23], AXFORD and CUNNOLD [1] and LAYZER [7].

The starting point is the continuity equation

$$(1) \qquad \partial n/\partial t = q - \alpha n^2 - \mathrm{div}(nV),$$

where t is time, n is electron density, α is recombination rate , q is production rate and V is ion velocity driven by the wind. This equation can be solved either analytically or numerically under proper boundary conditions for a given magnetic field, electron density, wind-shear and metallic ion concentration. It turns out that the main term is the divergence term operating on long living ions. Only metallic ions have such long lifetimes that Es layer formation can be explained . This has been verified empirically [10, 8, 25]. It is, however, shown by WHITEHEAD [24] that there still are open questions in the windshear theory.

The so called auroral zone types of Es differ drastically from the midlatitude types of Es. The main type is retardation Es, which is explained in terms of "particle E layer" seen at oblique incidence. Particle E is formed as the normal E layer but the ionization is caused by precipitating particles instead of solar UV- and X-rays. In the auroral zone these particles are 1-10 keV electrons, which ionize effectively at E layer heights [16]. The equation (1) can be greatly simplified by assuming equilibrium and neglecting the divergence term. The equation then takes the form

$$(2) \qquad q = \alpha n^2,$$

which is exactly the same as used in simple normal E layer modelling. This also shows that in case of retardation Es there is a direct relationship between the particle precipitation and the parameters of Es layer. In practice the situation is more complicated, because one must integrate over the energy range of incoming particles, take into account the pitch angle distribution and assume a proper recombination coefficient. Also it is by no means certain that one can always safely neglect the divergence term, because processes effective in the formation of midlatitude type Es layers may well be effective in the formation of auroral zone types of Es layers too. Examples of layers produced by auroral particle precipitation are given recently by BARON [2], who also discusses the physical background in some detail. Baron measured the layers by incoherent scatter facility in Chatanica.

The second auroral zone type is the so called auroral Es. It is formed by scattered echoes, which are usually oblique, and can have a great variety of forms. It never blankets nor shows multiples. Under the name "auroral Es", several different physical phenomena are included and they cannot be separated when the standard data are used.

There are two more high latitude Es types, i.e. slant Es and D layer Es, both of which are due to weak scattered echoes. Slant Es is studied from the Sodankylä data by OKSMAN [12] and its physical background and the worldwide occurrence are discussed by OLESEN [13]. D layer Es is seen during strong absorption events as a scatter from the D layer. Slant Es and D layer Es are not studied in this thesis.

It is clear that the name "Sporadic E" is given for a group of phenomena, which do not necessarily have anything in common. This makes the use of standard data difficult because in the parameters common to all Es layers, i.e. critical and blanketing frequencies and virtual height, several different physical phenomena are treated together. Even the use of Es types does not guarantee that these phenomena are separated. It is shown by SHAEFFER [17] that there exists flat type Es related to auroral processes although formally flat Es is dealt as a midlatitude phenomenon. On the other hand separation between different midlatitude types is often questionable, because they certainly are related to the same physical process but have different names mainly on the basis of the properties of the surrounding media.

It is also shown in this thesis, in paper IV, that at very high gain level a weak echo becomes visible in ionograms and resembles the echo from low Es layer. This echo has caused great difficulties in using the Sodankylä data, because it enters the data as low Es and dominates the statistics of Es parameters when the noise level is low. Examples of the phenomenon are given by TURUNEN [21].

In this thesis it is attempted to describe the behaviour of Es phenomena at Sodankylä in terms of physical processes. This means that the phenomena related to the same process are studied together. If a parameter is dependent on two or more physical processes, an attempt to separate these phenomena has been made when possible. This having been impossible, the parameter has been omitted in this study.

This thesis shows how the main Es phenomena behave at Sodankylä and what physical processes they are related to. It also shows some of the limitations in the present practice in interpreting ionograms.

3. METHODS

3.1. Data

The data used in this thesis had been measured at Sodankylä by an ionospheric sounder. This sounder is exceptional because of its automatic gain control. In most of the data studied in this thesis [papers II,IV, VI and VII] the gain control senses the noise level. In addition the receiver has high quality rhombic aerials and tuned rf-stage. In consequence the signal to noise ratio is good and all echoes above the noise level are seen on the recording. This is a great advantage during anomalously high absorption but during low absorption and at low noise level very weak phenomena are seen on ionograms. In Es studies problems arise because of a weak reflection from the bottom side of E layer. This echo forms in ionograms an echo pattern, which is similar to low Es. In consequence the data on low and flat Es are difficult to study. It also happens that weak scatter around E-layer echo, especially near foE, can saturate the receiver, which causes inaccuracies in blanketing frequency. These effects are summarized in paper IV and discussed also elsewhere by TURUNEN [21].

The critical point in Es studies is the interpretation of ionograms. This thesis is based on data exceptional in the sense that both the maintenance and the interpretation of ionograms have been carried out by the same persons throughout the studied period under the supervision of an ionospheric physicist.

The standard parameters interpreted from the ionograms for Es layers are Es type, virtual height, critical frequency and blanketing frequency. The virtual height gives for overhead Es layers with no retardation a good estimate of the true height. The blanketing frequency gives a good estimate of the maximum plasma frequency but the critical frequency does not seem to have so clearly defined physical meaning [15, 19]. It is clear that even the blanketing frequency cannot be exactly related to the maximum plasma frequency of the Es layer because it is slightly gain dependent [4], as shown in paper III.

In this thesis the standard ionospheric data from Sodankylä ionospheric station were used in all studies when possible. In cases, where better accuracy or special parameters were needed, special experiments were made. These experiments helped also in understanding the limitations of the standard data.

3.2. Methods of analysis

Diurnal and seasonal variations of Es parameters were studied from the standard data for the years 1958-1971, including in some cases the year 1972, too. The long term variations were studied from the same data by counting annual occurrences of parameters. The results and details of the analysis are described in papers IV and VI. Because of limitations in the standard data due to very high gain special studies were carried out especially for midlatitude Es behaviour using low gain soundings made simultaneously with normal soundings in summer 1973. These results are given in papers I and V.

The response of Es activity to magnetic storms was studied from normal soundings recorded during a single magnetic storm (paper II) as well as statistically using a list of published isolated substorms (paper VII).

Es echo amplitudes were studied in some selected cases. The equipment used was an automatic amplitude recorder, which measured the relative amplitudes of Es and F layer echoes. Some of the results are given in paper III. These results are, however, very preliminary and further study is needed. The data processing especially needs further development before large amounts of data can be studied in reasonable time.

These studies reveal the gross features of Es behaviour at Sodankylä and investigate the basic processes producing the group of ionospheric phenomena called Es. The methods used in this thesis do not allow a study of very detailed behaviour of those layers. It can be questioned whether such a behaviour can be satisfactorily studied at all using the standard ionospheric sounding data.

4. RESULTS AND DISCUSSION

4.1. Morphology of Es layers at Sodankylä

All the internationally classified Es phenomena, the equatorial Es layer excluded, are seen at Sodankylä. In this study two of the high latitude types, slant Es and D layer Es, were omitted because they are very difficult to study reliably from the standard data. The reason is that they reflect weakly and are not often seen, the statistics thus being poor and greatly affected by absorption and noise level. A special study taking into account all the factors the measurements depend on is needed.

The remnant part of Es activity can be divided into three groups on the basis of the physical phenomenon causing the Es layers. These are:

1) Midlatitude type Es activity, which includes the Es types h, c, l and f with the exceptions mentioned below. The main source of midlatitude type Es activity is the windshear generated by atmospheric tidal wave.

2) Auroral zone type Es activity, the main types of which are r and a types of Es. Part of the f type Es activity belongs to the auroral zone type Es activity, too. This Es activity is closely related to auroral substorms and the main ionization is caused by auroral particle precipitation.

3) Weak diffuse low type Es. This layer is not a real Es layer although it is counted as an Es layer in Sodankylä data. It is a very weak reflection and it never blankets. It is seen only under low noise conditions in high gain soundings. It looks like a nonblanketing low Es. This is why the data on low Es are difficult to use, the same being also true with the foEs and h'Es data from Sodankylä in the years when noise controlled automatic gain was used. The weak diffuse low type Es is probably caused by the steep electron density gradient in the lower part of the E layer.

4.2. Midlatitude Es activity

Midlatitude Es activity is a summertime phenomenon at Sodankylä. If the number of events is counted without giving any weight to the strength of the events the midlatitude types of Es form the main part of Es activity at Sodankylä for most years in the studied period, as can be seen from the results of papers IV, V, and VI. Possible exceptions are the years 1958-1961 when the number of c and h type layers was low and a large number of auroral Es layers were seen. In the years of very high sunspot numbers the overall Es behaviour was not so well defined as it has been afterwards. Contamination due to weak diffuse echoes is also strong.

Midlatitude type Es layers appear at Sodankylä in two distinct waves as shown in paper V. This behaviour is also clearly seen from the statistical behaviour of c and h type layers in paper IV.

The waves commence in the morning around 0800 hours local time and in the evening around 1700 hours local time. They are most easily seen in the virtual height of layers, which descends from about 120 km to about 105 km in 4-7 hours as shown in paper V. Basically these two waves are due to sequential Es, which is studied in paper I. The sequence is, however, seldom complete. At Sodankylä complete sequences are seen only in connection with the evening wave, which is stronger than the morning wave both in the occurrence frequency of events and in the values of blanketing and critical frequencies of layers. As seen from the papers IV and VI, the absolute number of these layers changes slowly from year to year. An overall change by more than factor of ten has occurred during the studied period at Sodankylä.

Because these layers are related to windshear it follows, that the windshear must be caused by a wave of about 12 hours period with roughly a constant phase relative to local time. This strongly supports the idea that the wave must be the semidiurnal component of atmospheric tidal wave.

Thus the midlatitude type Es activity has two diurnal maxima, one a little before noon and the other late in the evening. The maxima occur at different times depending on the parameter, which is used in the study. There is a third maximum around midnight both in the occurrence frequency of layers and in the critical and blanketing frequencies. This is partly due to enhancements in the long living part of low type layers formed during the evening wave, and partly due to layers having connections to auroral activity. There is nothing seen in the virtual height behaviour which could propose that a third wave similar to the morning and evening waves of midlatitude type Es layers exists in the night time.

The behaviour described above is not revealed in the contour maps for foEs > 5 MHz in paper IV. The reason is that this parameter is in summer time almost totally controlled by weak diffuse Es layers. Neither is it seen in the statistics of events having the blanketing frequency over 4 MHz because this parameter is totally dominated by auroral zone Es layers, mainly by retardation Es. This shows that it is dangerous to describe high latitude Es behaviour with a single parameter only.

4.3. High latitude Es activity

The main auroral zone Es types are retardation and auroral Es. They are night time phenomena with relatively small seasonal variation as shown in paper IV. This is the behaviour found everywhere in the auroral zone [20]. These layers are related to magnetic activity [9, 11].

In an earlier study on Es parameters from Sodankylä data by OKSMAN [11] it was found that retardation Es occurs when aurora is not above Sodankylä and auroral Es when aurora is overhead. Further, Oksman notes that distinction between flat Es and auroral Es is in many case caused by absorption. There are two points worth mentioning here. In the paper by OKSMAN [11] only discrete aurora is considered. Despite the absence of discrete aurora there may be diffuse aurora overhead although it is difficult to see from all sky pictures. Further Oksman has used a practice which seems to be common at auroral zone stations, i.e. the use of auroral type Es alone in case of scattered Es trace. In consequence blanketing Es layers are named auroral Es although this is definitely against the international rules for ionogram interpretation. Instead of using auroral type Es alone, one should use some of the several possible combinations of auroral Es, retardation Es, flat Es and particle E layer. Because there is place only for one critical frequency and one blanketing frequency, it is not possible to have all the information obtainable from the ionograms in the data when several Es layers are simultaneously present. This is a weakness in the the standard rules and its effects should be studied.

The best available parameter to describe the auroral zone Es behaviour seems to be the blanketing frequency because it is easy to interpret and gives an estimate for the maximum plasma density of the Es layer. The layers, which control the blanketing frequency data,are retardation Es, flat Es and particle E.

In this thesis the diurnal and seasonal variations of auroral and retardation Es are presented in paper IV. These layers are seen in the evening and night time sectors at the same time when Es layers with high blanketing power occur. Seasonal variation is quite small. If Es events are counted by using high threshold values in blanketing frequency, e.g. 4 MHz, the auroral zone types of Es layers almost totally dominate the statistics.

In papers II and VI the behaviour of Es parameters during substorms is described. Together with the results of paper IV it can be summarized that at times, when the station is under the auroral oval the blanketing frequency of Es increases at the onset of a substorm or even a little before indicating the onset of auroral particle precipitation. Maximum is reached shortly after the onset and the decay phase is slow and smoothly behaving. In 3-4 hours the quiet time level is reached according to median values. The critical frequency shows the same pattern. Because there is a wide local time sector covering at least the hours 1800-0300 at Sodankylä, when the blanketing frequency respondes to auroral substorms, the soft particle precipitation must have wide longitudinal extension. A special study based on data from several stations is needed to find out the latitudinal extension of sporadic E layers, which are related to auroral substorms.

In the summer the auroral substorm sometimes commences when a mid-latitude Es event is in progress. In these cases one to one relation between the substorm and the blanketing frequency of Es layer is lost. Frequently the midlatitude flat type Es changes to auroral flat type Es. Often the blanketing frequency rises and the echo becomes diffuse. These things were not studied in this thesis. It is however clear that before one can safely use the blanketing frequencies quantitavely as an indication of soft particle precipitation, the role of windshear generated accumulation of metallic ions in the formation of substorm activated layers must be studied.

4.4. Weak diffuse echoes

Severe difficulties in using the data from Sodankylä ionospheric station are due to the presence of very weak echoes in ionograms at times when the noise level is low. This weak echo is seen practically always during daytime hours in the summer and it controls the statistics of foEs > 5 MHz in paper IV. The behaviour of monthly medians of virtual height being also controlled by it, it was not possible to use them. The weak reflection is seen usually at heights of 100 km from the lower boundary of E layer. It never blankets, but scatter connected to it can saturate the receiver when very high gain level is used, thus preventing the normal recording of the stronger echoes, which have roughly the same virtual height. This is why the blanketing frequencies below foE are very unreliable in the Sodankylä data. The phenomenon is discussed in paper IV and examples of it are given by TURUNEN [21].

The weak diffuse echoes disappeared totally when the gain control method of the ionosonde was changed in April, 1974, in such a way that only echoes above -26 dB relative to the strongest echo are seen in the recording. Because the strongest echo is usually the o-mode echo from the totally reflecting layers it can be estimated that the effective amplitude reflection coefficient of the weak diffuse echoes is below 0.05.

Prior to April, 1974, these echoes were interpreted as low type Es at Sodankylä ionospheric station. It seems, however, that these echoes should not be considered as an Es layer.

It is not studied if the weak diffuse echoes are seen only at high latitude stations.

4.5. Long term variations of Es parameters

Yearly counts of parameters were used in the study of long term variations. Midlatitude type layers were studied by counting high and cusp types together. For reasons mentioned earlier it was not possible to include the Es types low and flat. Retardation and auroral Es were studied separately. The only frequency parameter possible to be studied reliably was the blanketing frequency with high threshold value. Results and discussion on the methods together with estimates on error sources are given in paper VI.

The long term behaviour in cusp and high type layers is peculiar. During the sunspot maximum years 1958-1959 a very small number of these layers were seen at Sodankylä. After a smooth and continuous increase a maximum was reached in 1970, which has about the same phase with respect to sunspot maximum as the years 1958-1959. The number of these layers increased by two orders of magnitude and the tests made on the data indicated that at least one order of magnitude change was real. In 1970 the main Es activity at Sodankylä was definitely midlatitude type activity. After that year the number of these layers has decreased.

It is evident that the number of midlatitude layers decreases sharply at latitudes near Sodankylä. Thus a small change in this latitude causes a dramatic change in the number of midlatitude layers. As seen in paper VI the change is smooth and does not seem to have any relation to the sunspot cycle.

The long term variation in retardation Es exhibits a clear sunspot cycle dependence at Sodankylä. There are double maxima around sunspot maximum years. The difference in occurrence frequency between sunspot minimum and maximum years is by a factor of three.

The yearly number of auroral Es events was very high in 1958-1960 compared with the remnant part of the studied period. The parameter is, however, very unreliable. The tendency is probably correct in the results. There may be physical significance in the fact that the long term variation in auroral Es is roughly opposite to the long term variation seen in midlatitude type layers.

An anomalous long term variation has occurred in the occurrence frequency of strongly blanketing Es layers. The maximum year was 1960 and the main minimum in 1969. Both these two years have roughly the same phase with respect to the sunspot cycle. This indicates that there is an anomalous long term variation in the occurrence frequency of strong soft particle precipitation events. Most of the layers at Sodankylä having blanketing frequency over 4 MHz are evening and night time layers connected to substorms, as can be seen from the results of papers IV, V and VII. An almost exactly similar behaviour is seen in the number of strong absorption events indicating that the same long term variation is present both in the strong hard precipitation events and in the soft precipitation events. Small absorption events correlate with the sunspot cycle. Unfortunately it is not possible to study from the available data if this is true also for weak particle precipitation events of low energy by using blanketing frequency data because of the limitations in the accuracy of data and contribution from midlatitude type layers at low blanketing frequency values. The long term variation of retardation Es shows, however, that correlation with sunspot cycle exists also in soft particle precipitation events when all events are counted, and this suggest that both at high and low energies the anomalous long term variation is limited to strong events only.

It is clear that even a study covering 15 years of data cannot reveal the main periods of the long term variations of Es parameters. Further it is clear that it is not possible to describe the behaviour with a single parameter. This is especially clear at high latitude stations, which record several different Es phenomena.

The origin of long term variations remains a puzzle. It is not possible by using data from a single station to say what part of the variation is due to a movement of "zones" or "boundaries" and what part is due to a change in the occurrence frequency and strength of events within the "zones". It is clear that something fundamental is still unresolved in the physics of atmospheric-magnetospheric system. If the long term variations are controlled by the sun as seems reasonable, then the part of the activity of the sun, which produces these effects must be partly or totally free from the correlation with the sunspot cycle.

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