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GEOPHYSICAL VARIATIONS AT SODANKYLÄ DURING A GEOMAGNETIC STORM 17—18 DECEMBER 1971

by

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Abstract

On the night of 17—18 December 1971, extremely bright auroras could be seen at Sodankylä and throughout Scandinavia. A detailed study has been undertaken of the geophysical phenomena observed at Sodankylä during this storm. The all-sky camera records, magnetograms, riometer records and ionograms obtained at Sodankylä that night are analyzed in detail. Published data from neighbouring stations have been examined to elucidate the extent of the geomagnetic storm and its effects on the upper atmosphere. It was noted that the occurrence of active auroral froms overhead was invariably followed by an increase of riometer absorption, and by changes in sporadic E. The analysis of this storm indicates that at least three substorms occurred during the main phase of the strom.

1. *Introduction*

Studies on the correlation of magnetic, auroral and ionosheric variations are not new. One such detailed study was made as early as 1953 and 1954 by MEEK, who established a relationship between the maximum elevation of auroral light above the northern horizon

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and the maximum amplitude of variation of H component at a high-latitude station in Saskatoon. He has also reported that certain types of sporadic E layers appeared more frequently during disturbances at this station. Using data obtained at College, Alaska, HEPPNER *et al* [2] established an association of absorption and Es ionization with aurorae at high latitudes. Their findings were as follows:

1) Es ionization increases at successively greater heights as an aurora approaches the College zenith from the north.

2) In the presence of certain non-pulsating auroral forms, Es ionization varies with changes in auroral form in a manner similar to the change in luminosity. Likewise, variations in the height of maximum ionization coincide with parallel variations in auroral heights.

3) Complete absorption is only slightly more frequent during non-pulsating auroras than in their absence, but predominates in the presence of pulsating auroras.

KNECHT [4] studied relationships between auroras and sporadic E echoes at Barrow, Alaska, and noted

1) a strong tendency for sporadic E echoes at frequencies over 7 MHz to be recorded when an aurora was near the zenith,

2) a direct relationship between brightness of inactive auroras and the peak frequency of Es echoes and

3) evidence for a correspondence of oblique Es-echo ranges with estimated slant ranges of visible auroral forms.

His observations bear out the view that ionization in the immediate vicinity of visible auroral forms gives rise to reflections of high frequencies.

MATSUSHITA [7] studied Es in high latitudes and electric currents during bay disturbances and geomagnetic storms and concluded that:

1) Retardation type Es and auroral Es are associated with geomagnetic bays and storms. The former is a thick layer, the latter is formed by field-aligned clouds; both are caused mainly by electron impact.

2) Slant Es echo in auroral latitudes and over the polar cap is due to a mode of radio propagation between ionized layers produced by electron impact.

3) Longitudinal electrostatic fields play an important role in the disturbed ionospheric current system at auroral latitudes at night. Es associated with bays correlates with the static field.

4) Es is occasionally associated with geomagnetic sudden commence-

ments, probably owing to electrons from the outer Van Allen belt or the solar plasma.

Maehlum [6] compared the various types of Es traces observed at many Norwegian stations with the geomagnetic recordings and K indices from Tromsö, and obtained the following results:

1) At Kjeller ($\Phi = 60°N$) the retardation type Es occurs most often during high values of K. At Tromsö it becomes less frequent as K increases.

2) The occurrence of the flat type Es is independent of K at both stations.

3) In Norway the visual auroral zone and the sporadic E auroral zone are at almost the same latitude. There is, however, some indication that the latter lies slightly south of the former.

4) The sporadic E auroral zone moves first southwards and later northwards during a disturbance. The rarer occurrence of retardation type of Es at Tromsö is explained by the fact that the sporadic E auroral zone is often situated south of Tromsö.

Hunsucker and Owren [3] made a comparative study of vertical incidence ionograms and all-sky camera photographs obtained at College. They found that

1) A high correlation exists between fEs and the auroral activity index derived from the auroral photograps; the correlation coefficient was over 0.5.

2) The relationship between the passage of an auroral band through the zenith and an increase of fEs can be seen from simultaneous ionograms and auroral photographs. Aurora at zenith seems to be accompanied by flat or auroral type sporadic E. Retardation type sporadic E appears when the aurora is at lower elevations.

3) Pulsating auroras are almost invariably accompanied by strong or complete blackout.

Oksman [11] made a detailed study of four individual storms in 1959 using all-sky camera records, magnetograms and ionograms obtained at Sodankylä. He observed that

1) The quiet auroral forms occur around the reversal of the geomagnetic storm.

2) The break-up of the aurora usually coincides with a large negative deflection in the H component in magnetograms.

3) Active auroral forms occur during the negative phase of H component.

4) The equivalent current system derived from the magnetograms grows in the north and moves south after the disturbance begins. During strong deflections in the H component it sometimes reaches a latitude somewhat south of Sodankylä. It returns north during the decay phase of the disturbance.

5) The current, which flows from west to east causing positive part in the H component and the current, which flows from east to west causing negative part in the H component, both seem to follow the pattern described above.

6) A low or flat type of sporadic E tends to occur before the start of the magnetic disturbance and after it ends, an retardation type of sporadic E is seen when the equivalent current is either north or south of Sodankylä. When the current is more or less overhead, an auroral type of sporadic E is seen.

7) foEs and fbEs grow together with ΔH regardless of the sign. In the event of retardation type Es foEs is usually less than 5 MHz and fbEs less than 3 MHz. In the event of auroral type Es, foEs is usually less than 6 MHz. Blanketing frequency can be as high as 6 MHz.

8) fmin grows during the negative part of the disturbance in the H component. During strong deflections complete blanketing often happens and low echoes can often be noted.

Morgan [10] found that large disturbances of the earth's magnetic field outside the auroral zone are often accompanied by intense sporadic E in the auroral zone. In general, he noted that an increase in sporadic E is preceded by a disturbance of the magnetic field, which suggests that a magnetometer can, to some extent, be used to forecast auroral sporadic E.

Reddy *et al* [12] studied the night-time auroral ionosphere over Fort Churchill, Canada, at different levels of magnetic activity, making use of rocket observations. They showed that the increase in magnetic activity is accompanied by:

1) a substantial increase of ionization in the height range of 90—140 km, and

2) by the appearance and rapid variations of small-scale ionization irregularities over a large part of the E region.

The semi-transparent portion of the auroral type Es in ionograms seems to arise from strong scatter-type reflections from irregularities. They further found that the blanketing frequency indicated the maximum plasma density in the auroral E region, while fEs is more sensitive to changes in the size and structure of the ionization irregularities.

The present paper is a study of various geophysical changes that occur during a strong auroral event. Though similar studies have been made earlier at Sodankylä by OKSMAN [11] it was felt worthwhile undertaking a study of this nature, especially in view of the fact that we have now riometer data available. The present study is confined to a single event and the emphasis is on the thorough understanding of this one event rather than a statistical analysis of several events.

2. *Analysis of the event*

Very bright auroras were seen over Sodankylä (geomag. lat 63.8°. geomag. long. 120.0) during the night of 17/18 December, 1971. It has been selected for the present study because the sky over Sodankylä that night was devoid of clouds and moon, with the result that the all-sky camera pictures are of exceptionally high quality. In addition, the magnetometer, riometer and ionosonde functioned perfectly throughout the event.

The data on the auroral band locations and background illumination obtained from all sky camera pictures are presented in Fig. 1 (a) as a function of local time. The ΔH and $\Delta Z/\Delta H$ values obtained from the magnetogram at five-minute intervals are plotted in Fig. 1 (b) on the same time scale. The ionospheric absorption of the cosmic radio noise at 27.6 MHz, measured by the riometer and computed in dB at five-minute intervals, is shown in Fig. 1 (c). The parameters foEs, fbEs and fmin were measured from the half-hourly ionograms and are plotted on the same time scale in Fig. 1 (d). No foF2 values are shown in this graph because the F-region traces were frequently blanketed during the event.

According to the all-sky camera records for that night, an aurora was first seen at 1745 LT*) in the northern horizon, where it remained for 15 minutes. But the magnetogram shows that ΔH began to increase at 1617 LT, at which time the local riometer also measured considerable absorption and fmin values were quite high. Simultaneously the foEs values were extremely high. This suggests that, before the visual auroral break-up, there must have been high energy particle precipitation to cause the increase in absorption. The fbEs values during this time, however, were quite small, indicating that ionization at E-region altitudes

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*) LT used in this study is UT + 2 hours.

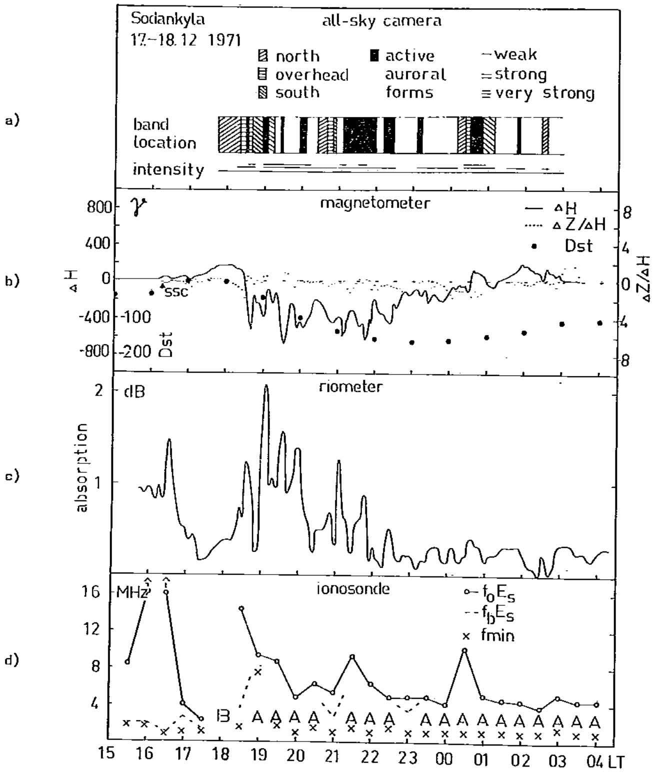

Fig. 1. Data from Sodankylä during the geomagnetic storm on 17/18 December 1971.

a) All-sky camera data, based on photographs taken at one minute intervals
b) Insensitive magnetometer, ΔH and ΔZ/ΔH, based on values at five-minute intervals. Dst is also shown
c) Riometer at 27.6 MHz, based on five-minute values
d) foEs, fbEs and fmin from ionograms, rescaled values,'A' indicates total blanketing and 'B' total absorption.

could not have been very strong. This suggests that the energy spectrum of the incoming particles during this time was hard. The large foEs values might have been due to the formation of small-scale irregularities in the E region altitudes.

A sudden storm commencement happened at 16.18 LT and this clearly triggered the storm as can be seen from Fig. 3. The preceding storm was at that time decaying. After ssc Dst values were almost zero

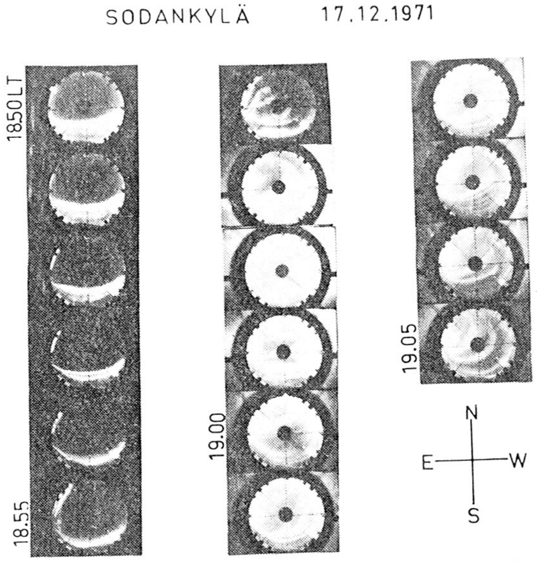

Fig. 2. All-sky camera photographs at Sodankylä, showing the extremely rapid and well defined onset of the substorm at 18.56 LT on 17 December 1971.

for two hours and the increase in Dst values started at the same time when aurora was seen at Sodankylä. It is impossible to say with which phenomena are the absorption and high foEs values in Sodankylä connected between ssc and the appearance of the first auroral arc. Part of the absorption is certainly due to earlier substorms but there may also be some absorption which is directly connected with ssc. It is tempting to connect the extremely high foEs values with ssc but the increase in foEs happened at least 18 minutes earlier than ssc and so the sporadic E layer at that time is probably at least partly connected with other phenomena than ssc.

At 1800 LT the auroral arc began to move southwards, reaching the sky directly over the station at 1823 LT. There it stayed until 1842 LT, expanding and occupying most of the southern sky. At 1832 LT a group of bands was visible directly over Sodankylä for about 10 minutes. The appearance of these bands at 1832 was followed by a very large decrease of about 500 γ in ΔH, and at this time $\Delta Z/\Delta H$ increased from negative values to almost zero. This suggests that the equivalent current system was directly overhead at the same time as

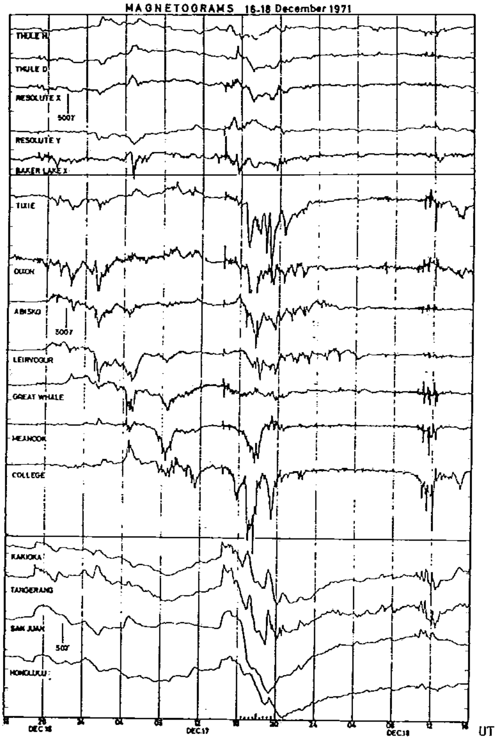

Fig. 3. Magnetograms for 16—18 December 1971, reproduced from the I.A.G.A. Bulletin No. 32 b.

the auroral bands. At this time the riometer recorded a sharp increase in absorption and the fmin and fbEs values began to increase and foEs also rose to very high values. A very interesting point was that ΔH displayed high values and the riometer recorded absorption only while the auroral bands were overhead. Soon after the bands moved away, the absorption decreased and ΔH inreased.

The appearance of the overhead auroral bands was associated with an increase in the overhead current system, an increase in ionization in the D region and the E region, and with the presence of irregularities in the E region altitudes.

The disappearance of the group of bands in the all-sky camera records was associated with a sudden decrease in the ΔH values and riometer absorption. Then at 1850 LT a single auroral arc appeared and ΔH decreased slightly. At 1856 a group of bands came rapidly from the east and, within some minutes, they occupied most of the sky. The effect of this can be noticed clearly in the riometer absorption, which increased very steeply by about 2 dB. ΔH decreased rapidly but $\Delta Z/\Delta H$ increased, which shows that the current system was moving southwards along with the auroral bands. At 1900 LT fmin was 7.0 MHz and F-traces were blanketed. At times between 1800 LT and 2100 LT there was large background absorption as measured by the riometer during which time fmin was low. This might have been due to the automatic gain control of the ionosonde, which smothers any small variations in fmin. Only very large increases in absorption, such as the one around 1900 LT are reflected in the fmin values.

Enhanced illumination was seen in the north-east sector of the sky a couple of minutes after 2000 LT, and around the same time ΔH decreased and $\Delta Z/\Delta H$ dropped practically to zero indicating an overhead current system. The riometer recorded a sharp increase of ionospheric absorption around this time and the fmin and foEs values showed a tendency to increase. The sky was not very active after 2010 LT. The auroral forms and illumination disappeared and absorption and magnetic activity decreased. The ionosonde observations however show that F region echoes were still blanketed and foEs values were around 5 MHz.

A new auroral arc appeared in the north at 2025 LT moving south, as had been the usuall pattern so far. It was accompanied by a decrease in ΔH. The arc was overhead at 2040 LT. It then broke into two bands, one of which moved southwards. Absorption increased around this time. At 2100 LT a group of auroral bands moved in rapidly from the west, after which the whole sky was illuminated so that no accurate description of the auroral forms was possible. ΔH continued to be large and $\Delta Z/\Delta H$ was small. A few minutes after 2100 LT there was a very sharp increase absorption and fmin, fbEs and foEs began to rise. Between 2115 and 2120 LT, the illumination was strong in the north and in the east, ΔH increased, and $\Delta Z/\Delta H$ increased. At 2125 a wide auroral band was formed overhead and it developed into a group of bands covering the sky. This situtation remained until 2157 LT. During this time ΔH decreased substantially, $\Delta Z/\Delta H$ was small and the riometer recorded yet another peak in ionospheric absorption and foEs, fbEs and fmin were fairly high.

The auroral activity decreased around 2200 LT, followed by an increase in ΔH values and a decrease in absorption, and foEs. After 2210 new auroral forms came in rapidly from the north and were overhead within a minute after which the whole sky was illuminated. At this time. the riometer showed very small absorption. ΔH values decreased at 2210, corresponding to the intense auroral activity around this break-up but for the first time during the entire event, the riometer did not show much increase in absorption. At 2225 a surge appeared from the west and disappeared in the east within five minutes. During this time ΔH decreased sharply and the absorption increased substantially. The ionogram for these five minutes recorded a typical auroral type sporadic E for the first time during this event.

From 2230 to 2310 LT only very weak auroral forms were seen. ΔH increased slowly and $\Delta Z/\Delta H$ increased correspondingly, indicating that the equivalent current system was not overhead. The ionospheric absorption decreased to a very low value and foEs and fbEs were only moderate. After 2310 LT an auroral band developed in the west and was overhead within one minute. Here it broke up into active forms and the whole sky was illuminated. This illumination lasted until 0010 LT during which time it shifted to the southern sky.

At 0010 LT an auroral arc appeared in the north. Moving slowly to the south, it was overhead at 0025. By 0037 the whole sky was full of forms. This lasted for a little more than ten minutes and at 0050 there was an overhead band moving to the south. This band disappeared in the southern sky at 0110, after which there was probably only weak illumination without any structure up to 0150 LT. Then some active forms were seen against the background of the illuminted sky for a few minutes. At 0225 LT a new band appeared in the northwest sector. This disappeared in the western sky seven minutes later without coming overhead. After 0300 there was some illumination in the sky, but no active forms. From then on the event slowly tapered off.

It is interesting to note that after midnight the ΔH values were positive and that auroral activity was not accompanied by an increase in absorption. Auroral activity was, however, seen in foEs.

3. *Discussion*

Akasofu [1] discusses in detail the manifestation of magnetospheric storm during geomagnetic storm which consists of the initial phase and the main phase. The first phase is characterized by a step function-like sudden increase and the second phase by a large decrease of the horizontal component; the first phase results from the compression of the magnetosphere by the interplanetary shock wave. The second phase results from the accumulated effect of the protons; thus:

$$\begin{tikzcd}
\text{Magnetospheric storm} \arrow[d] & = & \text{Compression} \arrow[d] & + \ \Sigma\,\text{Magnetospheric substorm} \\
\text{Geomagnetic storm} & = & \text{Initial phase} & + \ \Sigma\,\text{Polar magnetic substorm and Magnetic field of the ring current}
\end{tikzcd}$$

Thus a study of the major phase of geomagnetic storms, the main phase, is reduced to a study of an elementary and fundamental process; the magnetospheric substorm.

This pattern, described by Akasofu, can be noted in the event which is analyzed here. First of all, to confirm that the event studied here was a manifestation of a magnetospheric storm, the Dst values, which are a measure of the ring current strenght, are plotted in Fig. 1 (b). A sudden storm commencement occurred at 1618 LT and immediately after that we find an increase in ΔH values at Sodankylä. Dst began to decrease from about 1900 LT on by which time the ΔH values at Sodankylä were also negative and large. To identify the individual substorms, the magnetograms for 16—18 December obtained at sixteen different stations, including both equatorial and high latitude ones, are reproduced from I.A.G.A. bulletin in Fig. 3. From Fig. 3 it can be said that a substorm started at about 1850 LT and lasted until 2030 LT. The all-sky camera records clearly reveal the beginning of this substorm (see Fig. 2). The auroral arc can be seen moving south at 1850 LT and breaking into active forms at 1856, immediately after which there was an increase in background intensity. The ionospheric parameters foEs, fbEs and absorption were high during the substorm. Perhaps this substorm can be said to have started at 1856 LT and ended at 2030 LT when ΔH and riometer absorption reached low values by which time, too, the active auroral forms seen earlier had disappeared.

The second substorm seems to have begun a little after 2100 LT, when the pattern desribed earlier repeated itself. An auroral arc appeared again in the north, came overhead and broke into active forms almost exactly at 2102 LT. The ΔH values decreased and absorption increased sharply from this time on. This substorm seems to have ended at 2315 LT with the termination of active auroral forms and riometer absorption and ΔH again fell to low values. The sporadic E layer parameters around this time were also low. The second substorm was longer in duration than the first one but in terms of riometer absorption the first substorm was stronger. Both substorms seem to have had distinct time structures.

The all-sky camera records show that there was third substorm starting at about 0000 LT and ending around 0115 LT. However the riometer and magnetometer at Sodankylä do not show any activity corresponding to this. That is most likely because Sodankylä was by this time in the post-midnight sector and thus probably not under the instantaneous auroral oval. Even so foEs was large corresponding to this substorm in similar way than during the earlier substorms.

The absorption recorded by the riometer before sudden storm commencement at 1618 LT was not connected with the event studied here but was probably related to an earlier disturbance. The increase in absorption about 1720 LT to 1835 LT was probably connected with the growth phase of the event (MacPherron, [5]). Most probably, at this time, the particle precipitation causing D layer ionization, was overhead in a narrow zone because there was total absorption in the ionogram at 1800 LT but the riometer measured at the same time quite low absorption. There was perhaps a growth phase from 2030 to 2100 LT connected with the second substorm commencing at 2102 LT. Both the substorms began with an 'explosive expansive phase' at 1856 LT and 2102 LT respectively, when the auroral arc suddenly broke into active forms. The timing for the third substorm is more difficult but the breakup of this substorm was according to all-sky camera pictures before 0037 LT.

From the results obtained by seven rocket launchings during different phases of magnetic activity at Ft. Churchill Reddy *et al* [12] report that an increase in magnetic activity is accompanied by a substantial increase of ionization in the active height range of about 90 . . 140 km and the appearance and rapid variations of small-scale irregularities over a large part of the E-region. This is borne out in the present study by a tendency noted for fbEs and foEs to increase during the course of the substorms described earlier. The Es recorded was mainly that of type 'flat' except at 2030 LT, when retardation type Es was noted. This could also be scaled as night E layer because it was totally blanketing. It is interesting to note that retardation type Es appeared during the quiet period between two substorms. Auroral type Es was first noticed only at 2230 when the absorption was low and there was rapid movement of an overhead auroral surge. Oksman [11] has suggested that auroral type Es is often observed and scaled by many stations as flat type Es owing to the occurrence of high absorption during the climax of the disturbance. For this reason he has scaled all Es traces during a disturbance that were not of the retardation type as auroral type. We have, however, not used this type of scaling although it is clear that absorption can really have the effects described by Oksman. From 0000 to 0400 LT we noted totally blanketing retardation type Es which could equally well have been scaled as night E layer except at 0030 LT, when auroral type Es was seen. This indicates that there was continous electron precipitation in the keV range and that after the third substorm the flux of particles was quite constant as can be seen from foEs (or foE-K). Low absorption indicates that there was very small amount of high energy precipitation.

The ionospheric data from stations Kiruna (geomag. lat 65.3, geomag. long. 115.6), Lycksele (geomag. lat. 62.5, geomag. long. 111.7) and Uppsala (geomag. lat 58.5, geomag. long. 106.8) have been examined for the night of 17/18 December. Strong, totally blanketing sporadic E with large foEs values prevailed at these stations during that night. The totally blanketing sporadic E at Uppsala, however, lasted only from 2000 to 2400 LT, whereas at Kiruna, Sodankylä (geomag. lat. 63.8, geomag. long. 120) and Lycksele it continued throughout the night after the onset of the storm. The only exceptions are at 2100 and 2300 LT at Sodankylä but also at those times fbEs was very high. This probably indicates, that from 2000 to 2400 LT the particle precipitation had extension at least down to the latitude of Uppsala and that during the rest of the night the precipitation boundary was between Lycksele and Uppsala.

The riometer records obtained at Kevo (geomag. lat 66.2, geomag. long. 110.6), Kiruna, Oulu (geomag. lat 61.8, geomag. long. 106.1) and Nurmijärvi (geomag. lat. 57.1, geomag. long. 102.9) during this night have been examined. Unfortunately the Nurmijärvi recording could not be utilized until 2300 LT because of external interference. After 2300 it showed very little absorption. The Oulu recording could not been used between 1900 and 1930 LT. The riometer records obtained at the stations listed above show the start of the first substorm at Kevo, Kiruna and Sodankylä, but not at Oulu. The beginning of the second substorm can be seen only at Sodankylä and Oulu. This indicated that the second substorm occurred farther south than the first one. The third substorm could not clearly be seen in riometer recordings.

4. *Summary*

The magnetic storm connected with the sudden storm commencement which occurred 17.12.1971 at 1618 LT was very strong. According to the analysis described above there was at least three substorms which started at 1856, 2102 and approximately 0037 LT according to all-sky photographs taken at Sodankylä. The first two substorms were seen in magnetogram and riometer recordings at Sodankylä. All three were seen in Es parameters as an increase of foEs and fbEs.

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