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THE TRIGGER PHASE OF MAGNETOSPHERIC SUBSTORMS

The last few minutes of the substorm growth phase before the auroral breakup show features distinct both from the gradual growth phase development and from the rapidly evolving expansion phase. During this time the optical auroras fade, energetic particle precipitation into the auroral ionosphere decreases, and the auroral electrojets weaken. The 5—7 minutes before the auroral breakup when these effects are observed has earlier been termed "the substorm trigger phase". Here we report on initial results of a systematic statistical study of the trigger phase phenomena that includes both auroral and ground based observations as well as global magnetospheric and interplanetary observations. As an example, we present one substorm event selected from the collected database. In this event (5 October, 1986) the trigger phase was observed with a multitude of ground instrumentation, and for the first time also by the EISCAT radar.

Introduction

The energy loading during the substorm growth phase is usually seen in the auroral ionosphere as enhancement of the auroral electrojets as well as brightening and southward motion of auroral arcs [e. g., Pellinen and Heikkila, 1984]. Typically the growth phase begins after the southward turning of the IMF, which enhances the energy input rate from the solar wind into the magnetosphere [Baker et al., 1984]. During the following hour or so energy is stored in the magnetotail, which results in strong increase of the cross-tail current system, especially in the near-Earth region [e. g., Pulkkinen et al., 1992].

However, during the last 5—7 minutes of the growth phase the slow, linearly varying development is interrupted. This was first observed by balloon-borne *X*-ray detectors, which are sensitive to precipitation of ≥ 25 keV particles. It was found that before the substorm onset the equatorward motion of precipitation stops [Pytte and Trefall, 1972], the precipitation spectrum softens [Pytte et al., 1976; Pellinen et al., 1982], and the count rates of precipitating energetic particles decrease. Pellinen et al. also demonstrated that the decrease in the precipitation rate was preceded by a rapid, non-linear growth of the precipitation.

Pellinen and Heikkila [1978, 1984] and Pellinen et al. [1982] studied all-sky camera (ASC) pictures during late growth phases and found that in many cases the auroral intensity fades 1—2 min before the auroral breakup. Using ground magnetic and riometer data they were able to follow the simultaneous equatorward motion of the growth phase arc, the electrojet center, and the riometer absorption maximum during the growth phase. Within the last 5 minutes the equatorward motion stopped, simultaneously with the fading of the arc. Furthermore, it was demonstrated that the fading is associated with weakening of the westward electrojet [Untiedt et al., 1978]. Pellinen and Heikkila proposed that the two-phase sequence of rapid non-linear growth followed by quenching be termed the "substorm trigger phase".

The trigger phase phenomena have been reported in conjunction with several substorm events, but no obvious correlation with previous magnetic activity or other ionospheric conditions has been found. It has been suggested that the phenomena are related to either changes in the energy input rate from the solar wind (IMF conditions) or to local tail processes near the source of the growth phase arcs (tail stretching) [Pellinen et al., 1982], but neither of these ideas has been developed further. Here we present a database which will allow the study of these problems both statistically and in more detail event by event. Section 2 briefly describes the database, whereas Section 3 concentrates on one excellent event during which the precipitation gap was for the first time recorded also by the European Incoherent Scatter Facility (EISCAT). In the discussion section we outline few magnetospheric processes that may contribute to the trigger phase.

Statistical study

In order to study what fraction of substorms show signatures of the trigger phase and what are their common global characteristics, we went through 7 years (1982—1989) of auroral ASC-observations from Northern Finland (Kevo, Kilpisjärvi, Sodankylä, Muonio). We selected periods in the magnetic local time sector 2000—0100 MLT, during which the auroral activity conditions changed from quiet to active in the 15-min-averaged quick-look tables. The search yielded 445 events. For these events the EISCAT magnetometer cross data [Lühr et al., 1984] were examined. This network includes seven magnetometers in Northern Finland. For each event, the start time of the magnetic disturbance (in the *X*-component) were recorded together with the station, magnitude, and time of the maximum disturbance (with 50 nT accuracy). The magnetic disturbances were clearly associated with substorm development in 359 of the original list of events; the average disturbance occurred at 2245 MLT and caused a 320 nT maximum negative bay in the *X*-component (varying from 100 nT to 2000 nT).

EISCAT radar data catalogs and IMF-observations have been scanned to register events during which these data are available. It turned out that EISCAT-observations are available for 99 events and IMF-data for 116 events. However, the common database with both IMF and EISCAT observations is relatively small, only 29 events. Magnetotail probes have as yet not been included in the database.

Event study: 5 October, 1986

The latter part of 5 October, 1986 was relatively disturbed with three consecutive substorms (onsets at ~1130 UT, ~1630 UT, and ~1930 UT). Here we describe observations during the last substorm of the day. The auroral electrojet (AE) indices recorded an enhancement of both eastward and westward electrojets shortly after

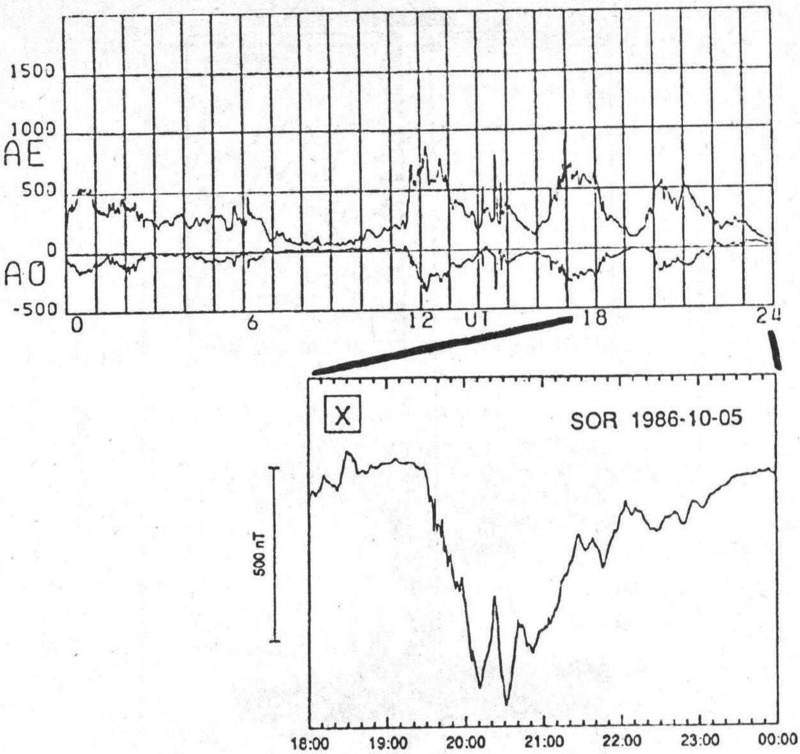

Fig. 1. Top: Auroral electrojet indices for 5 October, 1986. Bottom: SOR magnetogram (X-component) for 6 hours around the event discussed in the text

1900 UT, an onset at about 1930 UT, and a further intensification to ~500 nT disturbance at 2000 UT (Fig. 1).

During that period the EISCAT magnetometer cross, which covers the geographical latitudes from 66.8° to 70.6°, was located in the premidnight sector. The lower panel of Fig. 1 shows the Sorøya (SOR) magnetogram from 1800 UT to 0000 UT, the top panel of Fig. 2 shows the magnetic observations in a finer time scale. At 1800 UT the two northernmost stations still showed signatures of the recovery of the previous substorm: A weak and broad eastward electrojet extended to the north of the cross. This was gradually replaced with a weak westward electrojet during 1830—1900 UT, which may signify the Harang Discontinuity drifting over the cross. The westward electrojet moved slowly equatorward after 1900 UT, as is typical for the substorm growth phase. Five stations in the middle of the chain (geographic latitudes 68.0°—69.9°) recorded a localized enhancement of the westward electrojets at 1923—1924 UT. From about 1926 UT to 1929 UT this enhanced growth phase electrojet faded — because all components at all stations decreased from their earlier deviations, we conclude that this was a clear fading effect, and was not caused by the electrojet drifting southward or northward. After 1930 UT the magnetometers recorded a sudden onset of a negative X-bay, with typical characteristics of the westward travelling surge.

The bottom panel of Fig. 2 shows three selected ASC-pictures during the period of greatest interest. The growth phase arc visible in the first picture faded at 1928 UT (second picture), and the surge head came to the camera field of view at 1932 UT (third picture).

The middle panel of Fig. 2 shows the electron density observed by EISCAT. Until 1920 UT, the electron density was unstructured and the E-region maximum was at 110—120 km, the characteristic energy of the electrons was 2—3 keV. At

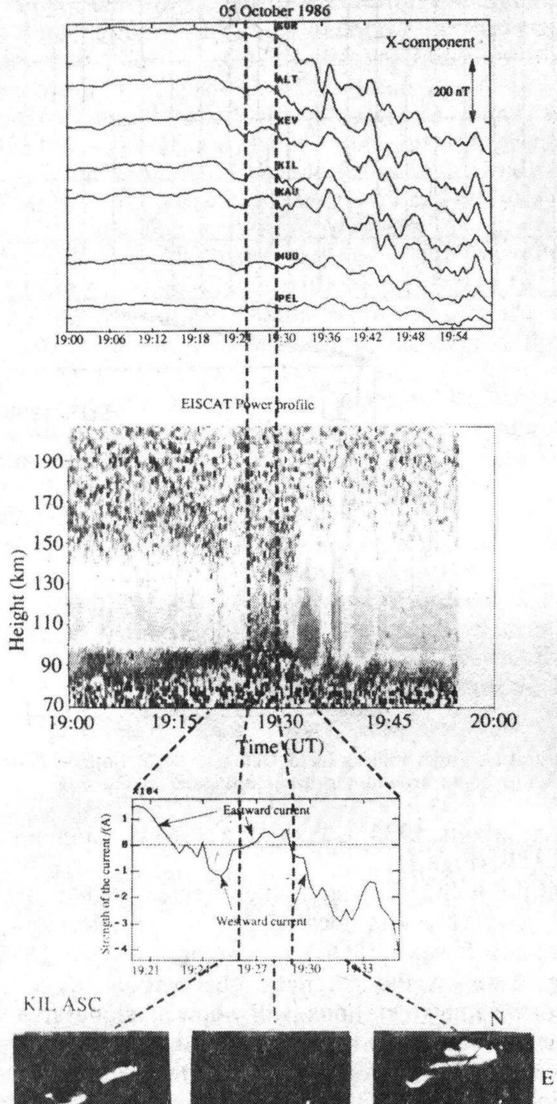

Fig. 2. Ground observations during the 5 October, 1986 substorm. Panels from top to bottom: EISCAT magnetometer cross data for the X-component. EISCAT power profile as a function of altitude. Model calculation of electrojet current strength. Note that the aero-current baseline is arbitrary, and the terms "eastward current" and "westward current" refer to used model currents only. The "eastward current" during the fading thus represents a weakening of the westward electrojet. ASC pictures from Kilpisjärvi

~1923 UT the precipitation became softer, as indicated by the increase in the E-layer altitude. Two minutes later the precipation intensity decreased and the maximum electron densities dropped below $1 \cdot 10^{11}$ m^{-3}, about a factor of two lower than was observed before 1920 UT. At 1932 UT the electron density suddenly increased when the westward traveling surge arrived into the EISCAT beam. The altitude of the precipitation maximum also decreased to 95 km, which shows that very energetic electrons were present. The lower border of the precipitation

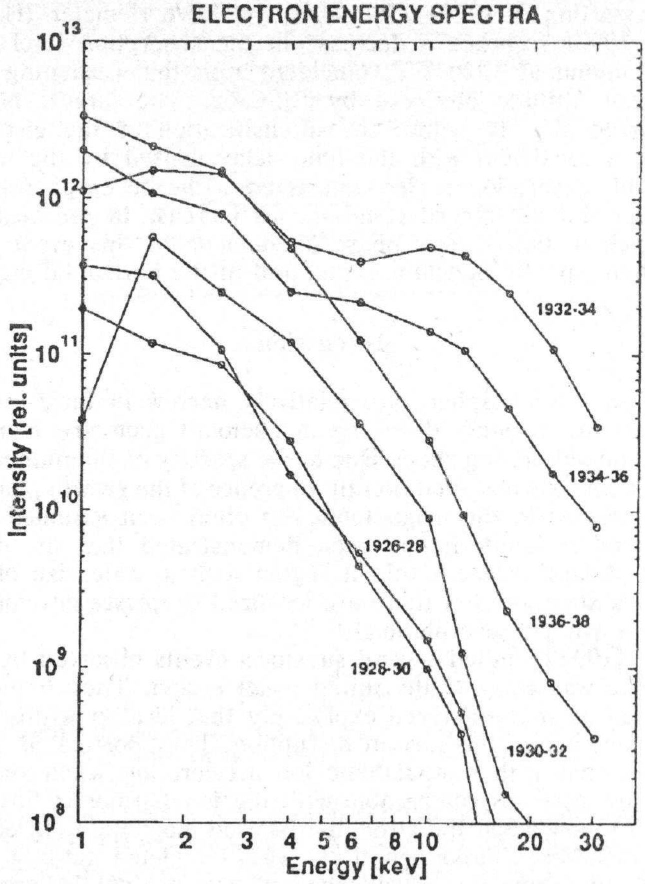

Fig. 3. Electron spectra at different times around the substrom onset on 5 October, 1986 as deduced from the EISCAT electron density observations

was 85 km, indicating that electrons with energies of about 100 keV were abundant in the precipitation. We have seen such intense precipitation only in three examples, in all cases the surge was formed very close to the EISCAT beam. There were some minor dropouts in the precipitation data at 1937 UT and 1943 UT that were accompanyed with decreases of the westward electrojet, suggesting that the entire substorm current wedge decayed and intensified quasiperiodically.

The total electrojet current was deduced from the magnetometer chain using a line current equivalent model. Even though the model is rough for detailed conclusions, the reduction in the current during the decrease of precipitation in the EISCAT data can be clearly seen. The optical fading occurred simultaneously with the electrojet weakening and the precipitation gap observed by EISCAT.

Fig. 3 shows electron energy spectra inferred from the electron density during the fading and the surge arrival. The two lowest curves show the low-intensity spectra during the fading. The intensity increased strongly at 1932—1934 UT and the precipitation became more energetic, which is seen by the much flatter shape of the spectrum. Within the surge head the dominating energy was between 10—20 keV, and the intensity of 10—30 keV electrons was four orders of magnitude greater than within the gap at 1926—1930 UT. Behind the surge head, after 1940 UT, the precipitation became softer again, but was slightly more intense than before 1920 UT.

The fading and intensification was also seen by additional ground instruments. The pulsation magnetometers (T. Bösinger, private communication, 1992) showed a decrease in the power beginning at 1926 UT, and an increase leading to the substorm onset starting at 1929—1930 UT. The Kevo riometer (H. Ranta, private communication, 1992) recorded a decrease in the absorption level after 1900 UT, leading to a minimum at 1920 UT coincident with the weakening of the electron density at 90 km altitude observed by EISCAT. The largest maximum in the absorption occurred slightly before the intensification of the electron density at EISCAT, which is consistent with the time delay caused by the westward motion of the surge. The absorption region connected with the surge was quite limited, the Ivalo riometer did not record simultaneous increase in the absorption.

Thus we conclude that trigger phase phenomena in this event were seen both in the precipitation pattern, optical auroras, and in the horizontal electrojet currents.

Discussion

Auroral arcs in the ionosphere are relatively narrow in their latitudinal extent, and thus even in the strongly diverging magnetotail geometry map to a localized source region in the tail plasma sheet. Due to the sparcity of simultaneous observations in the magnetotail and the observed overall coherence of the growth phase development, the current distribution in the magnetotail has often been assumed to be relatively smooth. On the other hand, it has been demonstrated that the onset process is very localized and takes place within a region with a scale size of 1 R_E [Ohtani et al., 1992]. This suggests that there are localized processes enveloped in the large scale coherent growth phase evolution.

Ohtani et al. [1992] studied several substorm events observed by AMPTE/CCE, where the satellite was close to the initial onset region. They found that in many cases the cross-tail current enhanced explosively (but locally) within the last minute of the growth phase before the current disruption. They postulated that this current growth was associated with nonadiabatic ion acceleration when the local fieldline radius of curvature becomes comparable with the ion Larmor radius. The substorm onset would then follow when the strongly distorted magnetic field becomes unstable to some plasma instability. Pulkkinen et al. [1992] modeled the large-scale cross-tail current development during the growth phase. They also studied the location of the boundaries of adiabatic motion in the model magnetic field. They found that the ions were non-adiabatic throughout large portions of the tail during most of the growth phase, but that the boundary between adiabatic and non-adiabatic motion moved Earthward by several R_E during the growth phase. The electrons, on the other hand, were found to be adiabatic throughout most of the growth phase, presenting a localized transition to non-adiabatic (chaotic) motion during the last few minutes of the growth phase. This has previously been suggested to trigger the ion tearing instability in a tail-like geometry [Büchner and Zelenyi, 1987]. More detailed observations and further development of the microphysical theory of the plasma sheet stability are required to determine whether it is the ions or the electrons that play the key role in the dynamical evolution of the tail. However, both studies indicate that at the end of the growth phase there are localized regions where the current density is very high, the current sheet is very thin, and the tail configuration is very stretched.

Pellinen et al. [1982] introduced the term "trigger phase" for a two-step process where rapid fluctuations in the ionosphere were observed before substorm onset. The first stage is associated with somewhat harder precipitation and north-south shrinking of the precipitation region, and the latter is characterized mainly by auroral fading-like features. To understand the development of the trigger phase, we need to examine the growth of the cross-tail (curvature) current caused by the transverse energization. The rate of particle energization by the cross-tail electric field can be given as $dW/dt = (2\mu_0 W_{\|}/B^2)\, \mathbf{E}\cdot\mathbf{J}_\perp$ [Pellinen and Heikkila, 1984]. In the magnetotail $\mathbf{E} \cdot \mathbf{J}_\perp > 0$, which means that particles gain energy. In an adiabatic process the energy increase from acceleration by the perpendicular electric field goes to the

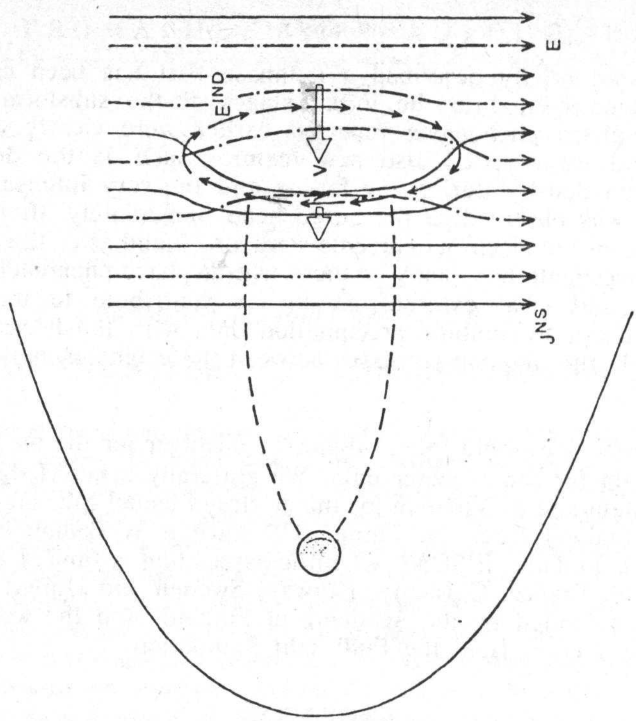

Fig. 4. Schematic picture of the cross-tail current development and effects of the inductive electric field [from Heikkila, 1981]

longitudinal component. For typical parameters in the magnetosphere during the late growth phase ($E = 0{,}3$ mV/m, $J = 10$ nA/m, $B = 5$ nT), the parallel energy of the particles increases so strongly that small pitch-angle ($\leq 10°$) particles precipitate into the ionosphere within a few seconds. The equation also shows that the energy growth is exponential in time if $\mathbf{E} \cdot \mathbf{J}_{\perp}/B^2$ stays approximately constant. At the beginning of the growth phase, E and J are small while B is relatively large, thus permitting the relatively slow growth phase development observed.

The rapid magnetic field changes during the late growth phase induce electric fields, whose role may be significant. It has been proposed that the neutral sheet current is filamentary and that the individual filaments are connected to auroral arcs as shown in Fig. 4. [Heikkila, 1981]. When this current is pinched and thus enhanced locally, a dusk-to-dawn directed induction electric field is created, which opposes the cross-tail electrostatic field, thus weakening it locally. This results in less efficient energization, and consequently decreases the precipitation, at all energies and for both electrons and ions. Before the formation of significant field-aligned currents, when the cross-tail current density increases in one region it must decrease in another region, since the current is described by $\nabla \cdot \mathbf{J} = 0$. Fig. 4 illustrates the principle of a current meander where in the region of decreasing current density the induction electric field will enhance the cross-tail electrostatic field. Therefore, in this region plasma convection should be faster than elsewhere. Mapped to the auroral oval this means that while the most equatorward arc has almost stopped and is about to fade before the breakup, there may be rapidly equatorward moving patchy auroral structures in the poleward sky. Such equatorward drifting arcs have been observed to merge with the equatorwardmost arc in several events recorded both by the ASCs and by the EISCAT radar.

Summary

In this paper we briefly described a database that has been created for the study of phenomena related to the initial stages of the substorm process. The substorm trigger phase phenomena reported earlier were clearly evident in the studied event, and we reported also new features such as the decrease in the ionospheric electron density during the fading and the very intense and energetic precipitation that was observed at the surge head immediately after the substorm onset. Fluctuations in the electrojet currents were also found after the auroral fading. It is our aim to investigate how many of these trigger phase phenomena are common to all substorms and what external parameters contribute to their occurrence. Especially, we attempt to combine precipitation data with the horizontal electrojet parameters to study the coupling processes between the magnetospheric source region and the ionosphere.

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