A substorm resulting from energy storage in the magnetosphere

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ABSTRACT. In order to study the problem whether magnetospheric substorms are directly driven by solar wind energy or result from unloading of such energy temporarily stored in the magnetosphere, it is necessary to investigate substorms following long quiescent periods and to observe solar wind parameters in proximity of the magnetosphere as well as many high-latitude ionospheric parameters with good temporal resolution.

In this study we present such observations obtained on November 29, 1984 by the AMPTE-IRM spacecraft just outside the bow shock and by the Sondrestrom incoherent scatter radar plus several other instruments in the earth's polar region.

We infer from the observations that solar wind energy was accumulated during a one to two hour period in the magnetosphere before being unloaded and dissipated in the polar ionosphere.

Key words: magnetospheric substorm.


INTRODUCTION

"A magnetospheric substorm is a transient process initiated on the nightside of the earth in which a significant amount of energy derived from the solar wind-magnetosphere interaction is deposited in the auroral ionosphere and in the magnetosphere" (Rostoker et al., 1980).

It is an interesting problem how the solar wind energy producing substorms flows through the magnetosphere until it is dissipated in the auroral ionosphere. There are two major schools of thought on this process: one is that the substorm is basically directly driven by the solar wind (Akasofu, 1979), and another is that a substorm begins with a growth phase during which solar wind energy is accumulated and stored in the magnetosphere for a while, before it is dissipated in the ionosphere (McPherron, 1970, 1979). This idea has been developed theoretically by Schindler (1974, 1975) who showed that a slow passive evolution driven by external conditions may become unstable in time, with catastrophic destruction of the equilibrium phase. The dynamic development is "active" in the sense that the onset and the time constants of this process are determined by internal properties of the system.

There has been much debate in the literature on these two viewpoints, and we wish, in this paper, to report on observations of a substorm event that casts light on this debate. The period we are investigating is from 0400 to 1200 UT (~ 02 to 10 MLT at Sondrestrom, Greenland) on November 29, 1984, during which an isolated substorm occurred.

During the period we are dealing with in this study, the AMPTE-IRM satellite was measuring the IMF just outside the bow shock on the morning side of the earth. Therefore we do not have to be concerned about solar wind propagation times, which often are sources of uncertainties in substorm studies when correlating solar wind events with events in the magnetosphere and polar ionosphere. In the study by Makita et al. (1985) for example it was assumed, that the solar wind velocity was constant and 400 km/s corresponding to about an 1-h time delay for the solar wind to propagate between the location of solar wind observations (ISEE-3) and the magnetosphere. Con-
sidering the possible variability of the solar wind velocity the uncertainty of this time delay may be several tens of minutes.

The Sondrestrom incoherent-scatter radar located in Greenland at 74° invariant latitude (Kelly, 1983; Wickwar et al., 1984) was operated during this study interval with 20 min resolution of electron densities and plasma convection velocities.

In addition to the observations made with the Sondrestrom radar and AMPTE-IRM, observations from DMSP-satellites, from ground based all-sky cameras and a meridian-scanning photometer are available from the neighborhood of Sondrestrom as well as, of course from magnetometers located anywhere in the world.

In the rest of the paper all indications of time without unit is universal time.

OBSERVATIONS

Solar wind conditions

On the morning of November 29, 1984, the AMPTE-IRM spacecraft was moving towards its apogee of 18.8 \( R_E \) in the pre-noon sector. At \( \approx 0300 \) (LT \( \approx 08 \)); geocentric distance \( \approx 16 R_E \) it crossed the bow shock and entered the solar wind. During the following 2 h, the solar wind conditions were quiet. At 0400, when the radar observations began, the solar wind velocity was 350 km/s, and the plasma density was \( \approx 10 \text{ cm}^{-3} \). The IMF situation is shown in figure 1. At 0510 a sudden change occurred in the solar wind; in particular, the IMF field strength almost doubled, and the \( B_z \) component became large and positive indicating an AWAY sector in the solar wind.

The solar wind, carrying an embedded magnetic field, has a total energy flux density

\[
U = \frac{1}{2} \rho V^2 + B^2 V/2 \mu_0
\]

where \( \rho \) is the mass density of the solar wind, \( V \) is its velocity, \( B \) is the strength of the IMF and \( \mu_0 \) is the magnetic permeability of free space. In figure 1 the two components of the solar wind energy flux density are shown in the bottom panel. The mass energy flux throughout the period is about ten times larger than the magnetic energy flux. From 0510 to 0640 there is a depression in the mass energy flux due to a slightly decreased plasma density (\( \approx 6.8 \text{ cm}^{-3} \)) and solar wind velocity (\( \approx 325 \text{ km/s} \)), and, although the magnetic energy flux is enhanced during this interval, the total energy flux is also lower than at any other time during the 8-h observation period.

The variation of the solar wind-magnetosphere energy coupling function (Akasofu, 1979)

\[
\varepsilon = V B^2 \sin^4 \left( \frac{\theta}{2} \right) I_0^2
\]

is also shown in figure 1. In this expression \( \theta \) is the polar angle of the IMF vector in the \( y-z \) plane in solar-magnetospheric coordinates \( = \tan^{-1} (|B_z|/|B_r|) \) for \( B_z > 0 \) and \( = 180° - \tan^{-1} (|B_z|/|B_r|) \) for \( B_z < 0 \). \( I_0 = 7 R_E \). Most conspicuous are (1) the abrupt enhancement at 0510 over more than two orders of magnitude and (2) the decrease at 0740 by a factor of ten.

Geomagnetic activity

The morning hours of November 29, 1984 were preceded by a geomagnetically very quiet period. November 28 was the quietest day of the month; the last three \( K_p \) indices of this day were all 1-, and the first two \( K_p \)'s of November 29 were 0 and 2.

Figure 2 shows geomagnetic activity during the period of interest here near the dayside auroral oval (New Aalesund), the nightside auroral zone (Great Whale River, Churchill, and Yellowknife), and at a nightside low latitude station (Pamatai). At \( \approx 0510 \) a sudden impulse occurs globally. There seems little doubt that it is caused by the solar wind change at that time, which was discussed above. Immediately thereafter the auroral electrojet starts to increase slowly in intensity, as indicated by the record from Great Whale River. At \( \approx 0612 \) a minor negative bay onset occurs in a limited area in the nightside auroral zone, apparently propagating from Great Whale River to Churchill, but not reaching Yellowknife. At \( \approx 0706 \) a sharp onset of a \( \approx 750 \text{ nT} \) substorm takes place near Yellowknife.

Inspection of several other magnetograms from various latitudes and longitudes confirm this description.
The high-latitude ionosphere

The Sondrestrom incoherent-scatter radar was operating from about 0400 to 1200 in the general survey mode described by Wickwar *et al.* (1984) alternating with elevation scans in the magnetic meridian plane at ~27° geographic azimuth. All observations were made with a 320-μs pulse giving a spatial resolution of about 50 km.

The general survey mode consists of a sequence of F-region measurements in 5 pairs of directions symmetric about the magnetic meridian plane and one about the magnetic field. The measurement parallel to the magnetic field. The determination of plasma drift velocities perpendicular to the magnetic field are made by combining these line-of-sight velocities (Foster *et al.*, 1981; Wickwar *et al.*, 1984). At low elevation angles, where velocities parallel to the magnetic field contribute little to line-of-sight velocities, pairs of measurements are combined. At higher elevation angles, the measurements parallel to the magnetic field are also included. Five sets of up to eight vectors, corresponding to the eight radar range gates, are obtained over a range of invariant latitude from about 68° to 81°. A gap exists between 73° and 74.5° because the radar beam is too nearly aligned along the magnetic field to derive meaningful perpendicular velocities.

The cycle time for the sequence of 11 positions is 15 min, with 2 to 4 min required for each set of vector determinations. The east-west spatial separation between points used to derive the vectors varies from 145 km at 200 km altitude to 358 km at 500 km altitude. Thus the vector determinations depend on the assumptions that the velocity field is constant for these time periods and homogeneous over these distances along contours of invariant latitude. A discussion of uncertainties in the derived velocities is given by Clauer *et al.* (1984).

The elevation scans start at 30° above the southern horizon and end at 30° above the northern horizon 5 min later.

Figure 3 shows the plasma drift measurements. Black and red vectors indicate convection with sunward and antisunward components respectively. From about 0400 to 0500 (02-03 MLT) a rather well defined convection reversal boundary is located at ~75°. The generally sunward directed plasma flow poleward of the boundary may be consistent with previous observations of sunward convection in the polar cap, when the IMF-$B_y$ component is northward (e.g. Burke *et al.*, 1979).

In fact the sunward convection at ~75°-77° stops at about the time (0520) when IMF-$B_y$ turns southward (Figs. 1 and 3). The convection between 0600 and 0800 is antisunward poleward of ~72°, and sunward south of that latitude. Around 0800 the reversal boundary moves several degrees poleward during about half an hour, and until 1200 (when measurements stop) sunward convection occurs in the whole latitude region (~70°-78°) observed by the radar.

These changes with time of the plasma convection are reflected in the electron density measurements made during elevation scans and displayed in figure 4, which shows electron densities in the E- and F-regions as function of latitude and time. From about 0400 to 0600 the electron density at 250 km's altitude is much larger than at 150 km. Measurements of the electron temperature (not shown) indicate that the F-region density may be due to precipitating soft electrons with average energy less than 500 eV. This precipitation is
Figure 4
E- and F-region electron densities measured with the Sondrestrom incoherent-scatter radar.

Figure 5
Electron densities observed along the earth's magnetic field by the Sondrestrom incoherent-scatter radar.
A characteristic feature immediately poleward of the auroral oval in the morning sector during magnetic quiescence (Makita et al., 1983). Obviously, this precipitation recedes toward the auroral oval rather abruptly shortly before 0600. This is confirmed in figure 5, which shows electron densities observed along the magnetic field. It is seen, that the density in the E-region and the lower F-region decreases around 0600 and abruptly increases again at ~ 0800.

In the terminology of Makita et al. (1983) the region of low-energy electron precipitation encompasses the polar cap. Thus, the deep minima in the E- and F-region densities between 0600 and 0800 poleward of 72°-73° indicate an abrupt increase of the size of the polar cap. The temporal resolution of the elevation scans allows us to say that the electron density depletion begins in the period 0548-0604 and ends between 0758 and 0814.

After about 0800 the electron density in the meridian scanned by the radar is similar at 150 and 250 km's altitude (fig. 4). The ionizing electrons are more energetic (one to several keV) as would be expected in the auroral oval proper.

A photometer scanning in the magnetic meridian plane was operated at Godhavn about 280 km NNW of Sondrestrom, in almost the same plane as the radar. The photometer observations at 6300 Å displayed in figure 6 show diffuse emission over the entire scan until 0600 with maximum intensity south of Godhavn. The observations at 4278 Å, which are not shown here, show that this emission is very low until 0800. This confirms that the ionization observed before 0800 is produced by soft particles. The region of maximum intensity south of Godhavn moves equatorward after 0530 about half an hour before the observed substorm onset. Very low intensities occur from about 0600 to 0800 in a wide region over Godhavn.

Observations from the all-sky camera network in Greenland locate the poleward border of the auroral oval at ~ 72.0° from 0430 to ~ 0730, when it rapidly moves poleward reaching 77° at 0820. The equatorward border of the oval is at ~ 68° until ~ 0610, whereafter it moves to lower latitudes, reaching its southernmost position at 64.5° (or lower) at ~ 0740.

Auroral arcs are easily detected by the radar. From the elevation scan measurements they are identified as electron density enhancements with steep horizontal gradients in the E-region. The minimum antenna elevation of 30° limits the latitude range in which arcs can be detected by the radar to 72°-76°. These observations show that particles ionizing the E-region (i.e. electrons of a few keV) occur from ~ 0440 to ~ 0630 at ~ 72.0°-72.5°. During the radar scan at 0753-0758 intense precipitation occurs at 73.3°-73.6°. All the following scans until 1200 indicate strong auroral particle precipitation between 72° and 76°.

An all-sky-camera was taking pictures every 2 min throughout the morning at Sondrestrom. It covered the latitudinal range from ~ 71° to 77°. Unfortunately a very cloudy sky prevented observations before 0744. After this time there were periods of clear sky during which the aurora was photographed until twilight began around 1020.

At 0744 a more or less magnetically east-west aligned arc occurs at 71.8°. It moves poleward with rather regular speed and is at 0758 located at 73.9°. This arc appears to occur at or close to the poleward moving convection reversal boundary mentioned above. During the following about two and a half hours several arcs often occur between ~ 72° and 76° embedded in the region of sunward convection.

Auroral images are available from DMSP F6 and F7 satellites. At ~ 0607 (a few minutes before the first small magnetic bay onset) F6 observes a diffuse emission over the entire polar cap region, and embedded within that region are a couple of discrete sun-aligned arcs. The discrete arcs at normal auroral oval latitudes (north of Anchorage) were quite weak; it should be noted that this situation existed nearly one hour after the large step function increase in $\epsilon$ shown in figure 1. At ~ 0620 (8 min after the first onset) F7 observes a well-defined arc in the evening auroral oval and a westward travelling surge, in agreement with the magnetograms in figure 2. At ~ 0800 (about 1 h after the second and major substorm onset) strong auroral activity is seen in the late evening sector by F7. The aurora extends over about fifteen degrees of invariant latitude up to ~ 76°. At ~ 0930 the evening as well as the morning auroral oval is observed by F6, both covering about ten degrees of invariant latitude. The locations of the poleward borders of the discrete aurora observed at 0620, 0800 and 0930 are shown in figure 7 by full lines. The squares indicate the positions of the most poleward aurora observed from Sondrestrom at 0620 and 0800. The dashed lines connect simultaneous observations in different MLT sectors.

In summary, these observations indicate that Sondrestrøm is located in the polar cap until ~ 0800 and in the auroral oval thereafter. Until about 0520 the plasma convection in the polar cap is rather disorderly with both sunward and antisinward convection. After this time the polar cap convection velocity is enhanced.
and antisunward only. From about 0600 to 0800 the polar cap E- and F-region electron densities are diminished, and so is the 6300 Å emission.

DISCUSSION

Fortuitous circumstances make this study unique. These are that solar wind observations were made just outside the earth’s bow shock, that the solar wind disturbance causing the substorm started very abruptly, and that the substorm occurred after a long period of geomagnetic quiescence. All this makes timing of the sequence of events quite accurate, and accurate timing is a must when the question is whether substorms are directly driven by the solar wind, or whether they result from temporary storage of solar wind energy in the magnetosphere and subsequent release of this energy.

Perrault and Akasofu (1978) and Akasofu (1981) suggested that geomagnetically substorms result when the $\varepsilon$ of the solar wind-magnetosphere dynamo reaches a critical level. According to Akasofu (1986) this level is approximately $6 \times 10^{10}$ to $1 \times 10^{11}$ W.

In this study $\varepsilon$ increases at 0510 abruptly to above $10^{11}$ W and observations indicate that solar wind energy flows into the magnetosphere from this time or shortly thereafter. At about 0520 the convection becomes better defined with clear antisunward flow appearing above 75°, and after ~ 0530 the convection reversal boundary moves equatorward.

Assuming that the high latitude region of antisunward convection is a region from which geomagnetic flux extends into the tail lobe of the magnetosphere, these observations imply an enhancement of magnetic flux and energy in the tail of the magnetosphere.

However, based on the magnetometer observations and auroral observations we define the substorm onset as occurring much later, at 0612. This is the time of onset of small negative bays in the $H$-components at nightside auroral zone stations. The DMSP F6 and F7 observations support this onset time. At ~ 0607 F6 sees no auroral substorm signature, but at ~ 0620 F7 sees a westward travelling surge. It is emphasized that neither the substorm onset at 0612 nor the onset of large negative bays at 0706 appear to be related to major changes in the IMF or $\varepsilon$.

Therefore these observations indicate that the substorm was not directly driven. Instead it appears that solar wind energy had to be fed into the magnetotail during approximately one to two hours until there was sufficient energy to be released by an unloading process.

Just as the sequence of events before and including substorm onset also is of importance for the question of whether a substorm is directly driven or is a result of an unloading effect, the timing of phenomena during the remaining part of a substorm is also of importance.

Again assuming that the dimension of the polar cap region with antisunward convection will provide at least a qualitative measure of the total magnetic energy in the magnetotail, Makita et al. (1985) investigated the relationship between the polar cap size, determined from particle measurements, the $\varepsilon$ parameter and the AIE index. They found that the total amount of magnetic energy in the magnetotail tends to grossly follow changes of these two parameters, and that the maximum dimension of the polar cap occurred during the period of the maximum AIE enhancement, i.e., during the maximum of the substorm expansion. Makita et al. (1985) concluded that this observation is in variance with the substorm model, that requires energy storage in the tail lobe and subsequent unloading. If that model were correct, then they would have found that the polar cap dimension decreased rapidly during the substorm expansion.

Returning to our observations, we find that the maximum of the ground magnetic disturbance at high latitudes is from about 0715 to 0845 (fig. 2), and that the polar cap boundary defined by the convection reversal boundary and by the most poleward auroral arcs quickly moves poleward after about 0740. Thus these observations, indicating that the polar cap shrinks during the substorm expansion, are signatures of the unloading model of substorms.

We may speculate that the fast shrinkage of the polar cap beginning at about 0740 is a direct consequence of the sudden decrease by a factor of ten of $\varepsilon$ at that time. This decrease of $\varepsilon$ is likely to imply a corresponding decrease of solar wind energy flux into the magnetosphere and unloading of energy accumulated in the magnetotail until then.

The situation may be analogous to common experiences with rubber balloons: when air is blown into a balloon, it expands as long as the input pressure is higher than the pressure inside the balloon. If the input pressure is decreased below the balloon pressure, the air flows out of the balloon again until pressure equilibrium has been reached.

Akasofu (1986) has criticized some observations used as evidence for the substorm model based on storage and unloading of energy. One of these observations is...
the so-called delay of about 30 min or more between a southward turning of the IMF and the corresponding rise of the AE index. One point made by Akasofu (1986) is that the AE stations are located in the classical auroral zone and therefore that these stations are not sensitive to disturbances which take place at higher latitudes. Akasofu (1986) rightly states that some magnetic disturbances may be detected at the highest latitudes before the AE stations indicate a substorm onset. Such magnetic disturbances in the polar cap, which are of the order 50-100 nT are, in our interpretation, caused by the enhanced antisunward plasma flow there following the southward turning of IMF or the equivalent rise in $e$. Therefore these magnetic disturbances in fact indicate the growth phase during which solar wind energy is being accumulated in the magnetotail.

Akasofu (1986) also mentioned that a high correlation between the cross-polar cap potential and $e$, obtained by Reiff et al. (1981), is supporting evidence for the primary importance of the directly driven aspect of magnetospheric substorms. We disagree with this statement for similar reasons to those given above. In our case, prior to substorm onset, there is both an enhanced antisunward flow and an expanded polar cap, which lead to an enhanced cross-polar cap potential. Therefore we also interpret this correlation as a signature of the growth phase.

In addition Akasofu (1986) discussed the delay of the response of a system with a large inductance. Probable values of inductances of 100-500 H in the magnetosphere and a resistance of about 0.1 Ω in the ionosphere will give time constants of 15-75 min. Akasofu (1986) suggests that such a delay must be subtracted from the observed delay before any other possible delay can be examined. However, if the observed delay is partly or wholly due to the effect of an inductance in the magnetosphere, we see no reason to exclude this effect, because such a delay is a result of energy storage in an inductance, which is as valid as any other storage mechanism.

Of course if the inductance of the magnetosphere were constant during a substorm event, the release of energy possibly stored in this inductance would likely follow an exponential function instead of an explosive release of energy which occurs at substorm onset. But the inductance of the magnetosphere may change during the substorm period as indicated by the changes in the polar cap dimensions discussed above and by Makita et al. (1985), and also because other parameters in the magnetosphere will change during the period that solar wind energy enters the magnetosphere. Such changes may create an unstable situation that could give rise to a fast release of stored energy.

In summary, we believe that the most significant aspects of the substorm development and recovery on November 29, 1984 are the following. After an extended period of magnetically quiet conditions, the solar wind power increased greatly. At that time the high-latitude convection became more ordered and the region of antisunward convection expanded. An hour later, the first indication of a substorm onset occurred, followed by another one another hour later. The level of magnetic activity remained high for 1.5 hours after the second onset. However, half an hour after this onset, the solar wind power decreased about a factor of ten and in coincidence the polar cap decreased rapidly in size.

In conclusion, we believe that these observations show that for an hour after the increase in the solar wind power, solar wind energy was being temporarily stored in the magnetosphere before the onset of substorm activity. Similarly, we believe that for an hour after the decrease in solar wind power, energy stored in the magnetosphere was continuing to be unloaded. These observations are not consistent with substorm activity directly driven by the solar wind.

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