The Use of Ground Magnetograms to Time the Onset of Magnetospheric Substorms

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The original definition of substorm onset was the sudden brightening of an equatorward auroral arc near midnight. Later, other phenomena were correlated with this onset and found to also undergo sudden changes. Because of this systematic relation these phenomena have also been used to time substorm onsets. Two such phenomena are the sudden intensifications of the westward electrojet in the midnight auroral zone and the development of field-aligned currents along field lines connected to the westward electrojet. These two phenomena are observed as characteristic magnetic deviations in ground magnetograms. In the midnight auroral zone it is the sudden beginning of a negative deviation (or bay) while at midlatitudes it is the beginning of a positive bay which has been used as the substorm onset.

Both experimentally and theoretically it has been established that the magnetic signature of substorm onset is spatially variable. In the absence of a perfect distribution of magnetic observatories timing errors may result from incorrect interpretation of limited data. An important question for substorm research is to what extent these errors have contributed to the development of incorrect phenomenological models.

A number of studies have established that many intensifications of the aurora cannot be observed magnetically at midlatitudes. Similarly, some disturbances, particularly events at high latitudes, cannot be observed magnetically by auroral zone observations. Another fundamental question is whether a phenomenological model based on data from the onset of magnetically detectable substorms is a correct basis for physical theories.

A third problem which has been only recently recognized is the frequent occurrence of fine structure within a substorm. Stepping substorms, multiple onset substorms and double substorms are names applied to events in which some of the phenomena normally associated with the classical model of a substorm reoccur with a frequency of 10–20 min, rather than the expected 2–3 hr.

1. Introduction

A fundamental question of magnetospheric research today is, what physical process causes the onset of a magnetospheric substorm? An answer to this question depends on the timing of substorm onset. Only if this time is accurately known can it be determined what physical processes are occurring at different points in space.

For example, PYTTE *et al.* (1976b), NISHIDA and FUJII (1976), and WALKER *et al.* (1977) show that in the midnight sector of the near geomagnetic tail a drop out of energetic electrons precedes substorm onset as defined by Pi 2 bursts and bays on ground magnetograms.

In the original concept of the auroral substorm (AKASOFU, 1964), substorm onset was defined as the sudden brightening of the southernmost auroral arc in the midnight sector. In extending the substorm concept, AKASOFU *et al.* (1965) showed that the polar magnetic substorm accompanied the auroral substorm, and that the magnetic signature of substorm onset was a sudden intensification of the westward electrojet beneath the brightening auroral arc. As pointed out by AKASOFU and SNYDER (1972), a physical variable such as plasma sheet thinning which is systematically correlated with sudden brightening of the aurora can also be used as a signature of substorm onset.

Because of their availability and relative simplicity, ground magnetograms have been used by many investigators to determine substorm onset (ROSTOKER, 1972b, 1974). Results obtained in this fashion have not always agreed with those obtained using auroral data, leading some workers to conclude that the "surest way" to define substorm onset is the one originally made by AKASOFU (AKASOFU and SNYDER, 1972).

In this paper we briefly review the technique of substorm timing using ground magnetograms. We particularly emphasize some of the pitfalls as these have led some workers to err in onset determinations. We also summarize recent developments in the concept of multiple onset substorms. Such substorms appear to account for many of the reported discrepancies in substorm timing. So frequently do such substorms occur that we suggest that present, idealized models of substorm morphology must be modified to include them.

2. Substorm Timing with Auroral Zone Magnetograms

Substorm timing using auroral zone magnetograms is based on the observations reported by AKASOFU *et al.* (1965), that a sudden intensification of the westward electrojet occurs under the same brightening aurora used to define the onset of the auroral substorm. As the auroral substorm develops the location and strength of this electrojet change systematically, expanding northward and westward with the aurora. Near the end of the expansion phase the equivalent ionospheric current system occupies nearly the entire auroral oval as shown in Fig. 1.

The existence of this current system is normally inferred from the magnetic perturbations in the horizontal component measured on the earth's surface. For example, applying the right hand rule to the currents in Fig. 1 at 0100 local time (LT) and 68° latitude gives a large southward ground perturbation or "negative bay in H ." Similarly at 2000 LT and 65° latitude one predicts a positive bay in H due to a weaker and more diffuse "eastward electrojet." The location of the electrojet in latitude relative to a ground station is inferred from the sign of the vertical com-

Fig. 1. Equivalent ionospheric current for westward electrojet. This model assumes the eastward electrojet near dusk is a return current for the westward electrojet (from AKASOFU *et al.*, 1965).

ponent. If the westward electrojet is poleward of the station the vertical component is out of the ground giving a negative component.

The onset of the substorm is normally inferred from a sudden drop in the H component at an auroral zone station just before midnight. Two examples are presented in Fig. 2. In both cases the sudden large drops at Great Whale were used as the signature of substorm onset (MCPHERRON, 1970).

There are numerous pitfalls in interpreting the magnetic data from a limited set of magnetic observatories. These pitfalls are primarily a consequence of the initial localization of the westward electrojet and its subsequent slow spatial development. For example, ROSTOKER (1972a), shows an example (his Fig. 3) in which the sudden onset at Fort Churchill is delayed 15 min relative to the onset at Great Whale, ≈ 600 miles to the east. Similar delays occur in the north-south direction. As an example (ROSTOKER, 1972), Fig. 13 presents data from a latitude chain illustrating a 20 min delay between two stations separated only a few degrees in latitude. Other problems arise when the substorm occurs on a contracted auroral oval. In such cases, as shown by AKASOFU *et al.* (1971, their Fig. 3b) no obvious signature is seen at standard auroral zone observatories although a station further north records a clear negative bay.

One tool which has been a great aid in interpreting auroral zone magnetograms is the latitude profile developed by Rostoker and coworkers. By comparing observed profiles of all three field components to model profiles it is possible to deduce a

Fig. 2. Magnetograms from an east-west auroral zone chain illustrating the determination of substorm onset using the sudden development of a negative bay in H (horizontal component) at a premidnight auroral zone magnetic observatory (Great Whale). Note both panels show double onset structure though only the left panel shows this explicitly (from McPHERRON, 1970).

number of characteristics of the electrojet current system. One characteristic which makes the timing of substorms particularly difficult is illustrated with this technique in Fig. 3. Three peaks in the perspective plot are separated by about 10 min and each satisfies the definition of substorm onset as defined above. Such “quasi-periodic intensifications” or “multiple onsets” are apparent in many auroral zone events (KISABETH and ROSTOKER, 1971, 1973, 1964). Figure 2 discussed above, shows two other cases in data from widely spaced auroral zone observatories.

The four problems outlined above inevitably lead to errors in the determination of substorm onset. In most cases the inferred onset will be later than the actual onset. An upper limit to the magnitude of such errors is of order 20 min, nearly the duration of a classical expansion phase. Greater timing accuracy can be obtained by using more auroral zone observatories so that the possible delays due to substorm expansion are reduced. In addition, as we discuss below, additional types of data may be used to time substorm onset.

Fig. 3. Dynamic development of the westward electrojet as recorded by a north-south chain of magnetometers. Successive peaks represent quasi-periodic intensification of the westward electrojet with a time scale of about 10 min (from WEINS and ROSTOKER, 1975).

3. Timing Substorm Onset with Midlatitude Magnetograms

Large substorms can be observed in midlatitude magnetograms as well as in auroral zone records. The expected midlatitude magnetic signature and its correlation with auroral zone effects has been well documented by AKASOFU and MENG (1968, 1969) and MENG and AKASOFU (1969). Figure 4 taken from this work shows the pre-midnight variations in H is positive (opposite to the auroral zone change) and about one tenth as large. Originally it was thought these effects were produced by ionospheric return currents of the westward electrojet (cf. Fig. 1). However, synchronous satellite data conclusively show field aligned currents are the primary source as discussed below.

Midlatitude perturbations in the D component depend significantly on latitude and local time (see Fig. 4). On the average in the northern hemisphere positive perturbations (east) are seen before midnight and negative perturbations are seen after midnight. The opposite sign is seen in the southern hemisphere.

The three dimensional current system responsible for both midlatitude and auroral zone substorm variations is shown in Fig. 5. This highly idealized model current system has an equivalent ionospheric current system virtually identical to that shown in Fig. 1 (BONNEVIER and BOSTROM, 1970; FUKUSHIMA and KAMIDE, 1973). Midlatitude magnetic perturbations produced by this current along a longitudinal profile in the northern hemisphere are shown in the bottom half of the figure. It is evident that the D component is very useful in determining the central meridian and width of the field aligned current system responsible for the electrojet.

Substorm timing with midlatitude magnetograms is based on the connection between the field-aligned currents and the westward electrojet. As a sudden intensi-

Fig. 4. The midlatitude signature of a double onset substorm as a function of latitude for a number of observatories in the premidnight sector (from AKASOFU and MENG, 1969).

fication of the electrojet occurs in the brightening aurora, field-aligned currents begin to flow feeding the electrojet. Magnetic perturbations of these currents are seen at midlatitudes as positive bays in H for stations inside the current "wedge." Onset is defined as the beginning of the midlatitude positive H bays.

An example of the use of midlatitude magnetograms in substorm timing is presented in Fig. 6. Vertical-dashed lines represent times chosen as substorm onset. As shown by McPHERRON *et al.* (1973b), the times for this event correspond to the onset of auroral zone negative bays as well. This is not always the case as auroral zone magnetic onsets may appear to precede the midlatitude onsets as discussed by McPHERRON *et al.* As discussed below, however, such cases seem to be examples of

Fig. 5. An idealized model of the field-aligned currents connected to the westward electrojet during a substorm expansion. The bottom panel shows the expected magnetic signature along an east-west midlatitude chain of magnetic observatories. Central meridian, angular extent and strength are the most important parameters of this current system (from CLAUSER and MCPHERRON, 1974).

multiple onset substorms for which the initial onsets are too weak to be observed at midlatitudes.

There are numerous problems associated with the use of midlatitude magnetograms, especially when only a few stations are used. One of the greatest problems is interference by other current systems. Since the field-aligned currents are far from the midlatitude observatories, perturbations due to other current systems can be of comparable amplitude. These include ionospheric currents driven by solar heating, magnetopause currents responsive to the solar wind dynamic pressure and the ring current created during magnetic storms.

If such effects were absent, midlatitude observatories would still be hampered by lack of sensitivity. Magnetic perturbations of weak substorms are below the noise level of most existing midlatitude observatories.

Another serious problem is caused by the partial ring current. This current is centered near the dusk meridian and opposite in direction to the expansion phase current system of Fig. 5. Unfortunately, these two current systems frequently develop simultaneously. Because the effect of the partial ring current is a negative

Fig. 6. Magnetograms from an east-west chain of midlatitude magnetic observatories illustrating substorm onset determination. The characteristic signature is the onset of positive bay at a near midnight station (black dots) (from MCPHERRON *et al.*, 1973b).

bay in H it is possible to misidentify the minimum of the negative bay as the onset of a positive bay if only data from the dusk sector is used. This can be seen in Fig. 6 for the second and third substorms if one uses only the data from Guam (GU) and Kakioka (KA).

As in the auroral zone, multiple onset substorms are a cause of some difficulty (CLAUER and MCPHERRON, 1974). For example, in the midlatitude data of Fig. 4 two onsets are clearly present in both the H and D components. Since it is often the case that one onset is much weaker than the other it is not obvious which onset to choose. Frequently multiple onsets may be separated by times short compared to the duration of a typical substorm. In such cases the requirement that substorms have only one onset has led some investigators to choose as "the onset" the one after which the largest magnetic perturbations occur. This choice can easily lead to "errors" as large as 20 min.

4. Multiple Onset Substorms

The concept of a multiple onset substorm appears to be a considerable departure from the substorm concept originally described by Akasofu and coworkers or from the model presented by KAMIDE and MATSUSHITA (1977). As shown above, however, there is ample evidence in the literature that such substorms are a rather frequent occurrence. Figure 7 taken from the work of ROSTOKER (1968) illustrates the mutual

Fig. 7. An example showing the close correlation between the onset of auroral zone negative bays, midlatitude positive bays and Pi 2 bursts (from ROSTOKER, 1968).

relation between auroral zone negative bays, midlatitude positive bays and Pi 2 bursts (see companion paper by Rostoker in this issue) during a double onset substorm. It is now well established that every major substorm onset is accompanied by a midlatitude Pi 2 burst. As discussed by SAITO *et al.* (1976) this correlation provides a useful tool for timing substorm onsets at midlatitudes overcoming the sensitivity problem mentioned above.

In recent work by PYTTE *et al.* (1976a), it has been established that almost every Pi 2 burst in a multiple onset sequence is accompanied by the usual ground signature of a substorm onset including a westward traveling auroral surge (also see WEINS and ROSTOKER, 1975; SERGEEV, 1974). This fact has led some workers to suggest that each onset is a discrete substorm separated by as little as 10–15 min (KISABETH and ROSTOKER, 1971, 1973, 1974).

Ground magnetic data showing a sequence of four onsets is plotted in Fig. 8 and Fig. 9. Vertical lines show times of Pi 2 bursts but this clearly corresponds to

Fig. 8. Auroral zone magnetograms in three local time sectors organized by magnetic latitude. Vertical lines show multiple onsets determined by Pi 2 bursts. The Z component is used to infer the location of the electrojet relative to each observatory (from PYTTE *et al.*, 1976a).

the definitions of auroral zone and midlatitude onset times as well. Auroral data for these events show sudden auroral brightening after each burst, and subsequently, westward traveling auroral surges (PYTTE *et al.*, 1976a).

At the present time there is some disagreement about the current systems associated with multiple onset substorms. WEINS and ROSTOKER (1975) suggest that during a sequence of onsets new westward electrojets of localized extent are being formed in a sequence of discrete westward and northward steps. PYTTE *et al.* (1976a) on the other hand suggest that a train of westward propagating surges is generated and that each surge is accompanied by a segment of westward electrojet. KAMIDE *et al.* (1977), however, feel that their "double substorm" has a second poleward expansion formed inside the disturbed region of the first and weaker substorm.

5. A Phenomenological Model for Multiple Onset Substorms

In the substorm model summarized by AKASOFU (1968), the time between expansion onsets is long compared to the duration of the expansion phase. However, the recent work shows that in some substorms the separation of expansion phases is shorter than their expected duration. These observations indicate a need for a new phenomenological model of substorms.

Fig. 9. Midlatitude magnetograms for the same multiple onset substorms shown in Fig. 8. Positive bay onsets are well organized by Pi 2 and correspond to auroral zone onsets of the preceding figure. The D component is used to infer the location of the central meridian of the substorm current (cf. Fig. 5) relative to each station (from PYTTE *et al.*, 1976a).

In a phenomenological model outlined by the author and coworkers (MCPHERRON *et al.*, 1973b), the substorm model was modified by inclusion of a growth phase (see also IJIMA and NAGATA, 1972). This phase is one of energy storage preceding substorm onset. Initially the observations of growth phase phenomena were claimed to be expansion phase features (AKASOFU, 1972). Later it was recognized these phenomena do occur and were most likely a consequence of dayside erosion, flux transport, etc., as discussed theoretically by CORONITI and KENNEL (1972a). However, it was argued that these features did not precede every expansion onset so a new name, reconfiguration of the magnetosphere was introduced to describe the growth phase sequence (AKASOFU and KAN, 1973).

As pointed out by MCPHERRON *et al.* (1973b) and CAAN *et al.* (1973), the original growth phase model applied only to isolated substorms or the first substorm in a sequence of substorms. Our view is that the full sequence does not repeat between successive onsets but must precede the first onset in a sequence. We suggest in addition that the classic recovery phase does not follow every successive onset but must follow the last onset.

If this view is correct the westward traveling surge and associated expansion is the fundamental entity which replaces the original concept of substorm. Our

present view is that the growth phase is a consequence of a southward turning of the interplanetary magnetic field and a reconfiguration of the magnetosphere. Westward traveling surges are generated by a sporadic release of the energy accumulated during the growth phase and, of course, during preceding westward surges. Recovery phase is a consequence of northward turning of the interplanetary magnetic field (IMF) and a return of the magnetosphere to its quiet state. We emphasize that

Fig. 10. Satellite observations contrasting plasma sheet behavior at two radial distances during multiple onset substorms. Drop out of energetic particles (interpreted as plasma sheet thinning) seems to precede each onset in the near earth region (from PYTTE *et al.*, 1976b).

this model distinguishes between the recovery following a westward surge and the recovery caused by the return of the magnetosphere to a quiet state.

The exact sequence of events during a “substorm sequence” depends on several factors. First is the IMF which must remain southward to accumulate energy in the tail. Second is the size and spacing of substorm expansions (westward surges) which release stored energy. Third are possible surge triggering mechanisms for example, sudden impulses (KOKUBUN *et al.*, 1977 and references therein); sudden northward fluctuations of the IMF (CAAN *et al.*, 1976); or possibly onset of instabilities in field-aligned currents (CORONITI and KENNEL, 1972b).

Since the IMF is usually fluctuating it seems likely that there will be many cases in which all the stored energy is released in a single surge. This would constitute a “classic substorm” in the sense that it has a growth, expansion and recovery phase. This is by no means the only sequence which is likely to be observed, as multiple onset sequences seem to be a very frequent occurrence.

6. Discussion

In previous descriptions of the growth phase model it has been suggested that magnetospheric reconfigurations lead to substorm onset. The suggested mechanism is plasma sheet thinning brought about by a demand for closed field lines in the dayside reconnection region. There is some evidence that thinning is important even in multiple onset sequences (PYTTE *et al.*, 1976b; NISHIDA and FUJII, 1976; WALKER *et al.*, 1977). In Fig. 10, data is presented for two satellites on the same meridian near midnight. The closer satellite, OGO-5 at $-12.7 R_E$ records gradual dropouts in energetic particles prior to each onset. In contrast Vela 4A at $-17.4 R_E$ records only a single dropout after the first major onset. These observations suggest that each onset is preceded by plasma sheet thinning in a localized region of the near geomagnetic tail.

To determine whether such thinning is of causal importance will require careful studies of future satellite data. Such data must be organized by accurately determined substorm onset times. Ground magnetograms will play an essential role in the determination of these times. The improved magnetometer networks presently under development (LANZEROTTI *et al.*, 1976) will considerably reduce errors in these determinations. However, the most accurate results will be obtained by combining the three major sources of information, auroral, pulsation and ground magnetic data.

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