Challenges of multi-spacecraft missions to end the substorm controversy

R. L. McPherron and T.-S. Hsu

Abstract: Magnetospheric substorms are one of the most important phenomena that occur in the Earth's magnetosphere. Substorms are caused by magnetic reconnection between the interplanetary magnetic field and the Earth's dipole field. Reconnection on the dayside is usually followed within an hour by reconnection in the tail. Isolated substorms consist of three phases: growth, expansion, and recovery. The process causing the onset of the expansion phase is not known. One model postulates it is reconnection that occurs first at 22 Re down the tail. Pile up of reconnection flows in the inner magnetosphere then causes the onset of the expansion phase. The other model postulates that some other process first disrupts the tail current in the inner magnetosphere and this creates the onset. This process launches a rarefaction wave down the tail that minutes later initiates reconnection. It has not been possible to identify the process causing onset because there are insufficient spacecraft and ground observations to determine the time of onset and direction of propagation. The Themis mission consisting of five spacecraft and numerous ground stations is designed to solve this problem. However, there are questions concerning whether a sufficient number of "perfect substorms" will be observed by Themis in its two-year lifetime. In this paper we estimate the probability of observing the "perfect substorm" and determine how many such events are likely to be seen. Depending on the assumptions we make we obtain between one and ten such substorms.

Key words: Magnetospheric Substorm, Expansion Onset, Themis Mission.

1. Introduction

The magnetospheric substorm is a sequence of processes in the Earth's magnetosphere during which energy is extracted from the solar wind and deposited in the magnetosphere and the ionosphere. Substorms are caused by the process of magnetic reconnection which allows two magnetic fields separated by a current sheet to connect to each other. In the Earth's magnetic field this happens when the interplanetary magnetic field (IMF) turns southward antiparallel to the Earth's dipole field at the sub-solar point of the magnetopause. Dipole field lines that were previously closed are opened and connected to the IMF. The solar wind carries these field lines over the poles and adds them to the lobes of the magnetic tail. Eventually these open field lines reconnect at the center of the tail and return to the dayside. If nightside reconnection did not occur all dayside magnetic flux would eventually be removed.

An isolated substorm driven by a short interval of southward IMF consists of three phases [8]: growth, expansion, and recovery. The onset of the expansion phase is signaled by the sudden brightening of the aurora around midnight near the equatorward boundary of the auroral oval. Within 1-2 minutes of this brightening, onset signatures consistent with magnetic reconnection are seen in the tail. The question that has not been answered is whether reconnection is the cause of the auroral brightening or a consequence.

Presently there are two main theories for the cause of substorm expansion onset. The first called the near-Earth neutral line model [1] postulates that thinning of the plasma sheet during the growth phase creates conditions allowing tail reconnection. Jets of plasma produced by reconnection flow parallel to the tail axis, one jet is Earthward carrying northward magnetic field, and the other is tailward carrying southward magnetic field. Within minutes after reconnection begins the Earthward jet piles-up in the inner magnetosphere creating the substorm current wedge that diverts tail current into the ionosphere as well as other effects characteristic of the expansion phase [14]. The alternative view is that some other process originates in the inner region and disrupts the tail current causing the current wedge characteristic of the substorm expansion phase [5]. This current disruption process generates a rarefaction wave that propagates down the tail initiating magnetic reconnection some minutes after expansion onset [6, 15].

Despite many years of study it has not been possible to resolve this controversy. There are several reasons for this as noted by [12]. First, the time for information to propagate between the two suggested regions of onset by either fast flows or waves is of order 2-3 minutes. Second, the cadence of modern measurements is too slow and of the same order as the time delays caused by propagation. Third, there are not a sufficient number of spacecraft in the tail at any time to unambiguously determine the direction or speed of propagation. As a consequence the proponents of the two main models remained fixed in their convictions and the controversy is unresolved.

2. The Themis Mission

To resolve the substorm controversy Dr. Vassilis Angelopoulos successfully proposed a NASA Midex mission that will place five identical spacecraft in orbit to monitor substorms. The spacecraft will be moved into three different orbits with 1-, 2-, and 4-day periods. The distance of apogee for these orbits will be ∼30, ∼20, and ∼10 Re. Since the reconnection

Received 22 June 2006.

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site in the tail is most often initiated at ∼22 Re and the current disruption region is located near 12 Re this arrangement should bracket the region of space containing the two proposed onset mechanisms. In addition one spacecraft will be located in between the two sites to provide information about the direction of propagation of disturbances. This mission is named Themis ($\Theta\varepsilon\mu\iota\varsigma$) after the Greek god of justice who weights the evidence and decides the truth of a hypothesis. In this case the name is also an abbreviation for Time History of Events and Macroscale Interactions during Substorms.

In addition to spacecraft the NASA mission includes ground support from ten magnetometers located in high schools and community colleges in the northern part of the United States. Even more support is provided by Dr. Eric Donovan of the University of Calgary whose team will deploy 16 imagers across Canada. Combined with imagers in Alaska the THEMIS array has 20 ground-based observatories (GBOs). Each GBO includes a white light all sky camera and a host of support equipment such as a computer, GPS antenna, and a satellite dish.

3. A Search for the Perfect Substorm

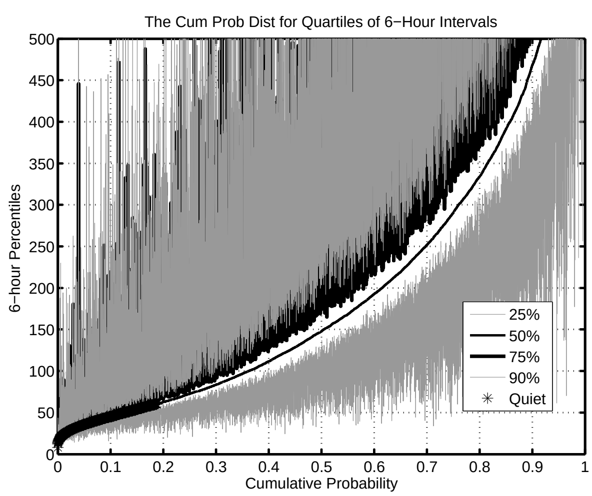

Fig. 1. Ten year's of cumulative distributions of 6-hour intervals of the AE index sorted by median value of each cdf. About 20% of all intervals are very quiet.

The primary objective of the Themis mission is to determine where the substorm expansion is initiated. This will be accomplished by placing the five Themis spacecraft in orbits such that all spacecraft are at apogee in the same meridian every four days. As the Earth travels around the Sun this meridian passes from dawn to dusk across the nightside allowing the spacecraft to simultaneously observe different regions of the magnetotail. Many substorms will be observed in the 3-4 months that the meridian is close to midnight. Some of these substorms will be so complex that it will not be possible to determine where or when the expansion began so it is important to identify "perfect substorms". By definition a perfect substorm is characterized by observations that unambiguously determine the location of onset. In the following paragraphs we attempt to make an estimate of how many such events are likely to be encountered each year.

For a substorm to occur it is essential that there be geomagnetic activity in progress. We can estimate the probability of some type of activity using 10 years of the AE index. Assuming that the spacecraft are optimally aligned for six hour intervals every four days we have calculated cumulative probability distribution functions (cdfs) of AE for successive 6-hour intervals. These cdfs were sorted in ascending order based on the median of each distribution. We identify any interval with a median below 60 nT and a ninth decile below 200 as geomagnetically quiet times. The results are summarized in Figure 1. They show that magnetic activity defined in this way occurs at least 83% of the time. Thus the probability that Themis will encounter geomagnetic activity on any pass is Pac = 0.85.

It has recently become evident that there are other forms of geomagnetic activity besides substorms. Steady magnetospheric convection (SMC) [13] is by definition a disturbed interval without substorms. The occurrence of SMC were studied statistically using the AE indices [7, 9] finding 2400 events in 10 years . The average duration of these events was about 2 hours corresponding to a total of 4800 hours of SMC in 10 years. This is an overall occurrence rate of ∼5%, or ∼7% of disturbed intervals. It has been suggested that this is an underestimate of SMC occurrence because this work did not include highly disturbed intervals that may be SMC.

It is clear, however, that substorms occur much more frequently than SMC. The waiting time distribution between onsets were determined by [2]. The upper panel of Figure 2 shows this probability distribution function (pdf). The mode of the pdf is 3 hours and the average time between onsets is 5.75 hours. With this separation we would expect about 15,234 substorms in ten years. If each substorm is about 4 hours long then substorms are present about 70% of the time. As a fraction of disturbed intervals this is about 84%. If instead we integrate this distribution to obtain the cdf shown in the lower panel we find that the probability of observing an onset in a 6-hour interval is also 85%. Thus we take the probability of observing a substorm during disturbed times to be Psub = 0.85.

One of the problems in substorm studies is the relatively high probability that the substorm onset will be preceded by a pseudo breakup. When a pseudo breakup occurs it is possible to question the association of phenomena in the tail with phenomena elsewhere, for example an Earthward flow preceding the main onset might be considered a consequence of the earlier pseudo breakup. To be classified as a perfect substorm the main onset should not be preceded by a pseudo breakup.

Both pseudo breakups and expansion onsets are associated with bursts of Pi 2 pulsations [10, 11]. Because of this we can use the occurrence of Pi 2 pulsations to assess the probability that the main expansion onset is preceded by a pseudo breakup. The results of such a study are shown in Figure 3. According to this graph about 58% of all substorms have the main onset associated with the first Pi 2 pulsation burst. Thus Pnopb = 0.58.

Another important consideration is the distribution of substorm occurrence in local time. Since substorm onsets do not occur on the dayside the probability of observing a substorm at sometime in the year is clearly less than $\frac{1}{2}$. Most substorm

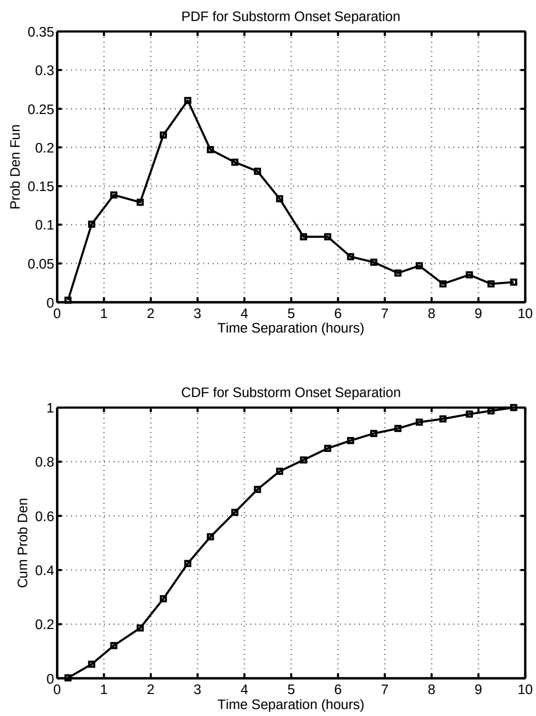

Fig. 2. Top panel shows the probability distribution for the waiting time between successive substorm expansion onsets obtained by [2]. The bottom panel presents the cumulative probability distribution obtained by integrating data in the top panel. There is an 85% chance that a substorm expansion will occur within a 6-hour interval.

onsets tend to occur just before midnight so the probability of observing an onset at other local times is much reduced relative to that at midnight. The local time pattern of substorm onset determined from Image satellite auroral images by [4] is presented in Figure 4. The distribution is peaked at 23 hours magnetic local time (mlt) and is zero throughout the dayside. The median of the distribution occurs at 22.4 mlt. There is less than 10% chance that a substorm will be seen before 21 mlt or after 24:30. We can roughly approximate this distribution by a uniform distribution of width four hours. In this case there is zero probability of observing an onset outside this interval so that the probability that Themis will observe a substorm onset at some mlt is Psloc $\approx$ (4/24) = 0.166.

The probability of observing a substorm at conjunction is the ratio of the time in conjunction to the time between conjunctions or Pconj = 6/96 = 0.0625. The requirement of conjunction significantly reduces the probability of observing a substorm.

Thus far we have tacitly assumed that all flows are in a meridian plane. Numerical simulations suggest that this is not the case. Observations also show that there can be significant east-west components of the flow velocity. As a crude approximation we assume that there is only one chance in 3 that the flow will be near the meridian plane of conjunction. If it is not in this plane then one or more of the spacecraft will not observe the flow and we do not obtain a perfect set of observations.

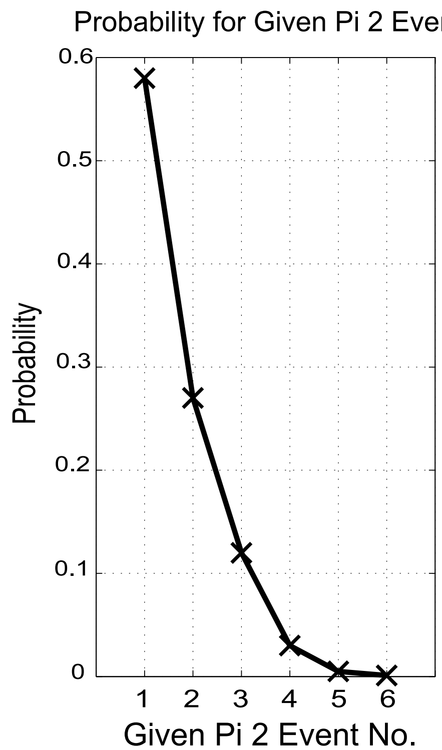

Fig. 3. The probability that a given Pi 2 during a substorm will correspond to the main onset of the expansion phase is plotted versus the sequence number of the Pi 2 in a single substorm.

Thus we take Pflow $\approx$ 0.333.

The Themis mission will use ground observations with all sky cameras and magnetometers to locate the magnetic local time and magnetic latitude of expansion onset. A magnetic field model will then be used to map this to the equatorial plane to determine whether the spacecraft are aligned in the same meridian as the onset. As shown by [3] it is likely that field-aligned currents will distort the mapping from that given by the model. As a consequence there is some possibility that a substorm supposedly in the conjunction meridian is actually located in another meridian. It is also possible that a substorm observed to be in a different meridian actually maps to the conjunction meridian. We do not know how to estimate the effect of distortion of mapping on the probability of good observations. For the sake of argument we arbitrarily assume that the mapping is correct 75% of the time, or that Pmap $\approx$ 0.75.

Determination of the onset meridian depends primarily on all sky camera observations of the aurora. If the weather is bad then it may not be possible to do this well, although it is often possible to see a change in auroral luminosity through thin layers of clouds. Magnetic modeling of ground magnetic perturbations provides and alternative method for locating the meridian of onset and Themis will have one of the densest collections of stations in existence to do this modeling. Finally, it should be recognized that not all equipment will be operational all the time. How the loss of one or more ground stations affects the probability of observing a perfect substorm is difficult to estimate. Collectively all of these factors will reduce the probability of observing the perfect substorm. We arbitrarily set the net probability of these factors to 90% so that Poper

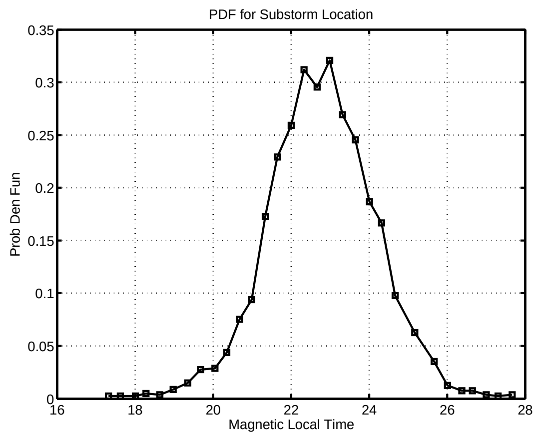

Fig. 4. Probability of observing a substorm at a particular magnetic local time [4].

≈ 0.9.

To estimate the total effect of all of the factors discussed above we assume they are independent. Then the total probability of a perfect substorm is the product of the individual probabilities. We thus have

$$PP = (Pact) * (Psub) * (Pconj) * (Psloc) * (Pnopb) * (Pflow) * (Pmap) * (Poper)$$

Substituting values estimated gives

$$PP = (0.83) * (0.85) * (0.0625) * (0.166) * (0.58) * (0.333) * (0.75) * (0.9) = 9.54 \times 10^{-4}$$

In one year we expect about 1525 substorms will occur. Multiplying by the aggregate probability we obtain a total of only 1.45 perfect substorms likely to be observed by Themis!

4. Discussion

Our estimate of the expected number of perfect substorms likely to be observed by the Themis mission is very small, only one per year. However, note that most of these factors are poorly known and it is easy to obtain more optimistic results. For example if we take into account the dwell of the spacecraft at apogee we can double the number of hours of conjunction to 12 hours. Also, our estimates of the probability of aligned flows and mapping problems may be too pessimistic and we can increase these probabilities. It may not be necessary to reject all substorms preceded by a pseudo breakup increasing this factor. Making less pessimistic assumptions we get 9.7 very good substorms.

If pessimism is justified we can be certain that data obtained during only one substorm will not convince the proponents of either of the two substorm models. On the other hand ten ”perfect substorms” all displaying the same behavior should be sufficient to convince most researchers that one of the models is correct. However, it seems more likely that Themis will provide an unprecedented collection of new data that rather than solve all the problems of substorm physics it is more likely that Themis will reveal additional details concerning the complexity of substorms.

Acknowledgments

The author would like to acknowledge support for this work from an NSF Space Weather Grant ATM 02-08501, from a Los Alamos IGPP Grant #1224001054, and from the CISM project funded at the University of Colorado in Boulder by the STC Program of NSF under Agreement Number ATM-0120950. The author also thanks Dr. James Weygand for providing the data used to generate Figure 4 and YaSong Ge for his help in converting this manuscript to LaTex. The AE indices were obtained from WDC-C2 in Kyoto, Japan.

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