Pi 2 Timing of Substorm Expansion Onset Using THEMIS Ground Based Observations and Other Data

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Abstract

We use data from over 100 ground stations to determine the onset of a substorm which occurred shortly after the THEMIS spacecraft began recording data. We show that the expansion onset at 11:10:30 UT on March 23, 2007 can be determined from Pi 2 pulsations to about ½ cycle (± 30 seconds). Profiles of onset times along different arrays suggest there are three distinct regions of Pi 2 excitation. These are the polar cap, auroral zone, and midlatitudes. Activity is seen first at highest latitude, next in the auroral zone, and last at midlatitudes. Polar spacecraft auroral images agree with the Pi 2 onset showing that Pi 2 pulsations measured over a large array of magnetometers can be used to time substorm onset relatively accurately in the absence of ground and satellite observations of the aurora. Furthermore we demonstrate that the delay in Pi 2 onset and signal strength is consistent with propagation away from the meridian of onset.

Introduction

The five THEMIS spacecraft were launched on February 17, 2007 [*Angelopoulos*, 2008]. In the initial coast phase the five spacecraft occupied very similar elliptical orbits following each other in a string of pearls configuration. During this phase the instruments were turned on, calibrated, and adjustments made to on-board software. On March 23, 2007 the spacecraft were commanded into a high data rate mode for the first time and serendipitously a substorm occurred as the five spacecraft were approaching midnight from the dusk sector. Data obtained at this time provide a unique opportunity to study a substorm observed with multiple spacecraft. The westward expansion of this substorm as seen by THEMIS is described by *Angelopoulos, et al.* [2008].

In addition to the spacecraft the THEMIS mission is supported by an extensive network of ground based observatories (GBO) covering all of North America with 22 all sky cameras and fluxgate magnetometers [*Harris and al.*, 2008; *Mende*, 2008]. The GBO stations are augmented by additional Education and Public Outreach (EPO) magnetometers (10); the Canadian Magnetic Observatory System (CANMOS) observatories (16); the CARISMA (Canadian Array for Realtime Investigations of Magnetic Activity) magnetometers (18); the Geophysical Institute Magnetometer Array (GIMA) with (>10) magnetometers; the McMac array in central US (8); the MAGDAS (MAGnetic Data Acquisition System) in the circum-pan Pacific region (20). Magnetometers at most of these stations acquire data at 0.5, 1.0, 5.0, or 10 second resolution. This resolution makes possible detailed studies of ULF waves associated with substorm onset as discussed by *Keiling and al.* [2008a].

The primary goal of the THEMIS mission is to determine whether substorm expansion onset occurs close to the Earth at about 10 Re through current disruption (CD) or further from the Earth at 20 Re through magnetic reconnection at a near-Earth neutral line (NENL) [*Angelopoulos*, 2008]. This is to be accomplished through alignment of the five spacecraft at apogee in a radial configuration with spacecraft at ~10, ~20, and ~30 Re. As the Earth moves around the Sun the spacecraft apogee cross Earth's magnetotail from dawn to dusk. If the onset of instability in the tail moves inward across the spacecraft array then the NENL model would be favored while outward motion favors the CD model. To achieve this goal it is essential to determine a precise substorm expansion onset time using ground and satellite observations of auroral luminosity and ground magnetic variations. A description of the particle and field modulation at THEMIS and their relation to ground observations is provided in several submitted papers [*Keiling*, 2008; *Keiling and al.*, 2008a; b].

The purpose of this paper is to use the extensive collection of high time resolution magnetometer measurements described above to time the onset of a substorm observed by THEMIS on March 23, 2007 and to estimate the accuracy of this determination. This time is determined by an analysis of magnetic fluctuations in the Pi 2 period band (45-150 s). The time obtained is compared to the times determined from auroral images on the Polar spacecraft (southern hemisphere), and all sky cameras in the THEMIS GBO network.

Experiment and Data Processing

The locations of five magnetometer arrays used in this work are shown by heavy lines with dots representing stations in Figure 1. Four arrays approximately follow fixed magnetic local times and include the 210° magnetic meridian (Japan), Alaska, Fort Smith, and Churchill/McMac. The fifth array is east-west across North America. These arrays were constructed from stations in different chains. The magnetic foot points of various spacecraft are indicated on the map by large colored symbols. These locations were calculated using the NSSDC Satellite Situation Center to trace field lines from the spacecraft to the northern Hemisphere using IGRF and Tsyganenko 89C for Kp = 3. The THEMIS footprints at 11:10:30 UT (time of expansion onset obtained below) are shown by red diamonds along the North Coast of Siberia. THEMIS C was leading, THEMIS E was following, and A, B, and D were close together between the other two spacecraft. The foot print of a LANL spacecraft was also in this region as shown by the blue circle (L97). Two yellow stars spanning the Bering Strait are the projection to the Northern hemisphere of the limits of the initial breakup observed by the UVI camera on the Polar spacecraft. Three black “X” in Alaska and Canada are the locations of three THEMIS GBO all sky cameras. The footprints of a LANL spacecraft (L89) and a GOES spacecraft (G11) in Western Canada are shown by a blue circle and green square respectively. Footprints of two other GOES spacecraft are shown further east in Central and Eastern Canada. Four red starts along the west coast of North America are 1-minute resolution magnetometers used to locate the central meridian of the substorm current wedge.

The solar wind and interplanetary magnetic field (IMF) were recorded by the ACE spacecraft at L1 and the Cluster spacecraft upstream of the bow shock at 11 hours local time. Geotail was almost exactly at the mid afternoon magnetopause. The solar wind and IMF data were propagated to the bow shock using the modified minimum variance technique [*Bargatze, et al.*, 2005; *Weimer, et al.*, 2003]. The IMF turned steadily southward (-4 nT) at ~09:50 UT and remained this way until 11:07:33. The substorm expansion began three minutes after the sharp northward turning.

Magnetometer data from the various stations were obtained from Internet web sites, e-mail file exchange, and the NSSDC. These data were in a variety of formats with different granulation, different naming conventions and different directory structures. Data from each station for an entire day were converted to a single binary Matlab data file containing data in a uniform format with a standard naming convention (statyyyymmdd). The station’s geographic coordinates were taken from original documents downloaded from different web sites. Magnetic coordinates were either obtained from these documents or calculated using the NSSDC Model Web Geographic to Centered Geomagnetic coordinate calculator.

The magnetometer data were passed through a sequence of processing steps illustrated by the curves shown in Figure 2. First, spikes were detected and flagged. Next all flags were removed from the data by spline interpolation. This was followed by 4-th order polynomial detrending of each component of the vector magnetic field. The X and Y traces from Poker Fat are plotted in the top panel. The processed data were then passed through a Butterworth filter with cutoff frequencies set at [1/150, 1/30] Hz to obtain Pi 2 waveforms. The filtered horizontal components X (north) [blue above base line] and Y (east) [red below] are plotted in the middle panel. Both signals have been rectified to double the frequency. The amplitude envelopes (black line touching extrema) were obtained by Hilbert transforming each signal. The last step illustrated in the bottom panel calculated the instantaneous power in the horizontal plane from the sum of squares of the two filtered horizontal components. Since this signal is not symmetric about zero a spline fit to successive extrema was used to determine the envelope shown by a black line.

The last step in the analysis was the interactive selection of the start time of Pi 2 activity using a graphics cursor. The time selected was the last minimum of signal power prior to a sustained increase in power above the background of the preceding 5-minute interval. It is apparent from examination of the figure that in this case a half cycle earlier or later than was selected (11:10:33) would be incorrect. Since the period of this wave was 88 sec this corresponds to a possible error of ± 44 s. In some cases the choice can be made to about ¼ cycle or an error of ± 22 s. This magnitude of error is supported by the consistency between adjacent stations described below.

A summary of the Pi 2 analysis for data from three North American and one Japanese array is presented in Figure 3. The earliest detectable Pi 2 fluctuations began in the polar cap at Cambridge Bay at 11:08:50 and Taloyoak at 11:09:33 (left panel). Onset in the auroral zone (65°-70°) was more than a minute later at about 11:10:30± 40 UT. Adjacent stations in the same chain have similar onset times, but stations at the same latitude in other chains differ by more than 20 s. The auroral zone delays are consistent with eastward propagation from Alaska to central Canada. The midlatitudes onset at 11:11:20 ± 20s is nearly independent of latitude and local time.

The Pi 2 power measured by each station is plotted in the right panel. Power is defined as the average horizontal power at the station in a 5-min interval following the onset. Peak power for every array occurs in the auroral zone at the same location as the electrojet. However, the peak power decreases in both directions away from Alaska.

During this substorm several other Pi 2 intensification occurred with onsets at 10:56, 11:18, 11:30, and 11:43 UT. The 10:56 Pi 2 was a weak isolated event not seen at all stations and is almost certainly a pseudo breakup. Magnetic fluctuations from this event were almost completely gone by the time of the main onset at 11:10:30. The 11:18 event was seen in Canada and Alaska as an enhancement of preexisting Pi 2 activity and is therefore hard to time precisely. This event was seen more clearly along the 210° meridian array through Japan where it produced very large enhancements of Pi 2 power starting at 11:18:08. The remaining two events are localized disturbances recorded at only a few stations.

We have identified the 11:10:30 Pi 2 onset as the substorm expansion onset for several reasons. First and most important it occurred at the same time as a UVI image taken by the Polar spacecraft in the southern hemisphere (see Polar keograms in Figure 3 of [*Angelopoulos, et al.*, 2008]). An image at 11:10:28 in the original data shows the beginning of an auroral brightening that expanded poleward in the next image at

11:11:41. The initial brightening occurred in the post midnight sector 0000 – 0130 MLT between 65 and 70 degrees magnetic latitude. It is this initial brightening that we have mapped into the Northern hemisphere across the Bering Strait (stars in Figure 1). The images at 11:17:49 and 11:19:03 show a sudden westward expansion of the aurora into the premidnight sector as far as 22 MLT [*Keiling*, 2008]. This expansion corresponds to the large Pi 2 seen in Alaska and Japan at 11:18:08. The second reason for identifying 11:10:30 as the main onset is that every available station shows a persistent enhancement of Pi 2 activity for at least 30 minutes after this time. In addition, stack plots of the original magnetic components after this time exhibit the characteristic pattern of a substorm current wedge. In the northern hemisphere perturbations in the Y (east) component were everywhere negative along the Fort Smith array and everywhere positive along the 210° meridian through Japan. InterMagnet stations at midlatitudes (red stars in Figure 1) show that the transition from negative to positive Y perturbations was between Victoria, B.C. and Sitka, AL. This indicates that the central meridian of the substorm current wedge was between these two observatories.

All sky camera data from Fort Yukon, Kiana, and Inuvik were processed producing movies, keograms, and plots of luminosity versus time. Our plots show that at the local time of Fort Yukon (magnetic midnight) the beginning of the auroral expansion was delayed at least four minutes relative to the onset determined by Pi 2 pulsations and the Polar images (c.f. paper by Mende et al.). We have also examined particle data from THEMIS spacecraft at 21 MLT, and from LANL spacecraft on both sides of midnight. At synchronous orbit, neither of the LANL spacecraft sees particle injection at the main onset, 11:10:30. Spacecraft G46 post midnight begins to see lower energy electrons at ~ 11:15, but the big injection occurred at 11:21:48 UT. In contrast the THEMIS spacecraft slightly outside synchronous orbit (particularly thc closest to the LANL spacecraft) see a gradual increase in electrons fluxes beginning at 11:10:30. However, a sudden increase in electrons occurred only after the expansion into this local time sector at 11:18 UT. In contrast to the delayed response at THEMIS, a GOES spacecraft at 0200 MLT observed an immediate change characteristic of a downward field-aligned current above and to the west of the spacecraft.

Discussion and Conclusions

The THEMIS mission is designed to resolve the controversy concerning the cause of the substorm expansion onset [*Friedrich, et al.*, 2001]. The hypothesis that the cause is an instability starting close to the Earth and moving outward (projection of the auroral expansion) is referred to as "current disruption" (CD) [*Lui*, 2001; *Lyons, et al.*, 2003]. The alternate view that substorms are caused by magnetic reconnection at a X-line ~ 20 Re down the tail is called the "neutral line" (NENL) model. For nearly 20 years it has been impossible to resolve this controversy because there were too few spacecraft and ground observatories, and existing ones were measuring at too low cadences. It is easy to show that the time for an Alfvén wave to travel from 10-20 Re outward, or a high speed flow from 20 to 10 Re inward is about two minutes. This is about the time between previously available satellite auroral images and the typical resolution of standard ground magnetograms. For the first time the THEMIS mission has provided multiple spacecraft in the magnetosphere, multiple ground stations with high speed auroral cameras, and high rate magnetometers.

In this paper we examined the utility of an extensive network of ground magnetometers in timing the main onset of a substorm expansion. Using approximately 100 magnetometers we found that a Pi 2 pulsation train emerging suddenly from a quiet background can be timed to accuracy better than ½ cycle of a Pi 2 pulsation, i.e. with accuracy of about ± 30 seconds. However, there are obvious delays in the onset time as a function of magnetic latitude and magnetic local time relative to the substorm onset meridian and magnetic local time. Pi 2 activity occurs first at very high latitudes, next in the auroral zone, and last at midlatitudes. It is also delayed as a function of local time away from the region of onset. Clearly a large array of magnetic observatories is needed to determine the time and location of initial onset.

For the substorm examined here we found that the world-wide onset of Pi 2 activity was rapidly followed by the appearance of signatures of a substorm current wedge. We call such an onset the "Main Onset" [*Hsu and McPherron*, 1998; *Hsu and McPherron*, 2002]. In this case our determination is supported by Polar images of auroral brightening which make the selection unambiguous. It is important to note that local ground observations of auroral brightening and expansion at magnetic midnight were significantly delayed relative to the main Pi 2 onset. Such observations cast doubt on the assertion that only auroral images can be used to time substorm onset. Obviously it is essential to be underneath the breakup aurora or observing from space for this to be true. We emphasize that particle injection at synchronous orbit was also significantly delayed relative to the main onset (>8 minutes), as were observations of particles and fields at the THEMIS spacecraft near 21 MLT (see papers by *Angelopoulos, et al*, [2008 and *Keiling and al.* [2008a]). However, a GOES spacecraft in the morning sector responded to the main onset almost immediately with signatures of a downward field-aligned current. We attribute this immediate response to the spacecraft being located below and close to the eastern edge of the downward field-aligned current in the substorm current wedge.

These observations illustrate the difficulties of resolving the substorm controversy with a limited set of observations. For the substorm examined here the THEMIS spacecraft were not yet in their final configuration, and the substorm onset was apparently located in the Pacific ocean west of the THEMIS ground array, so we are unable to draw definitive conclusions about the cause of the breakup. However, we have shown that Pi 2 pulsations measured with a large array of magnetometers can be used to time substorm onset relatively accurately in the absence of ground and satellite observations of the aurora. Furthermore we have demonstrated that the delay in Pi 2 onset and signal strength is consistent with propagation away from the meridian of onset.

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Figures

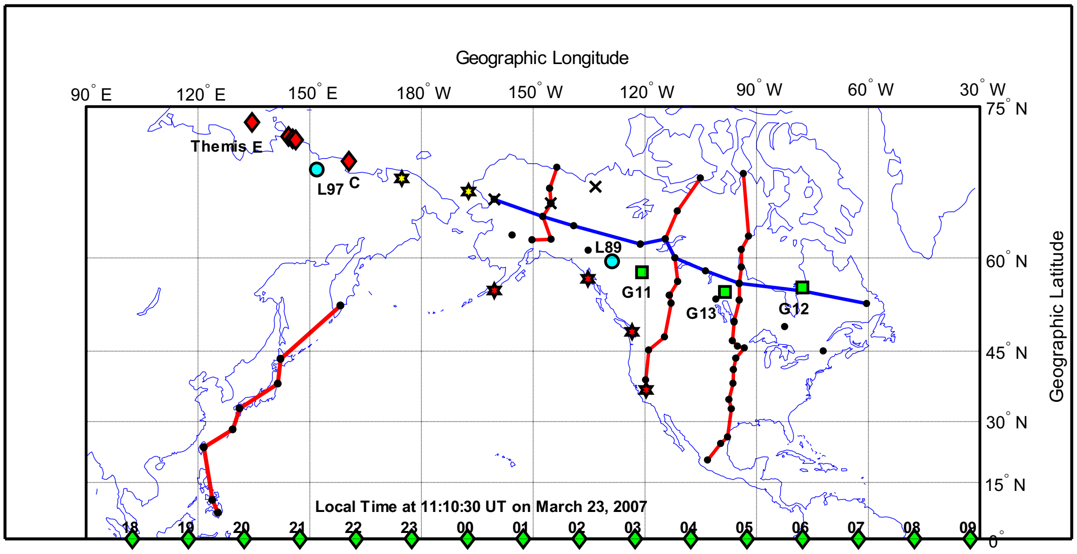

Figure 1. The location of magnetometer arrays are shown by heavy lines connecting black dots. Spacecraft foot points at 11:10:30 UT are denoted for THEMIS by red diamonds, for LANL spacecraft by blue circles, and for GOES spacecraft by green squares. The two yellow six-pointed stars are the projection of the auroral activation seen in the southern hemisphere by Polar spacecraft. Four red stars show location of midlatitudes observatories that define the central meridian of substorm current wedge. The green diamonds depict local time at the equator at the time of substorm expansion onset.

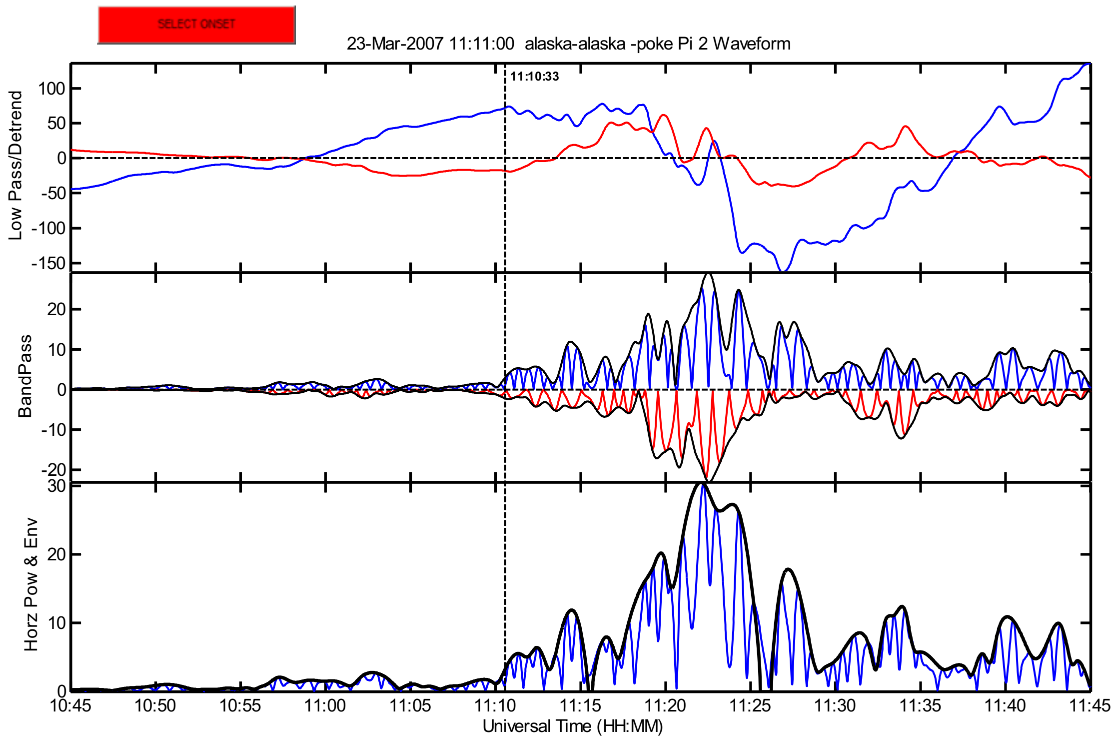

Figure 2. Poker Fla Pi 2 pulsations are presented. Top panel show detrended original data. Middle panel shows absolute value of X-component (blue line above baseline) and negative of absolute value of Y-component (red line below baseline). Heavy black lines define the envelopes as determined by a Hilbert transform. Bottom panel presents the instantaneous horizontal power with an envelope determined by cubic spline fit to extrema. The vertical dashed line defines onset of Pi 2 activity in all three frames.

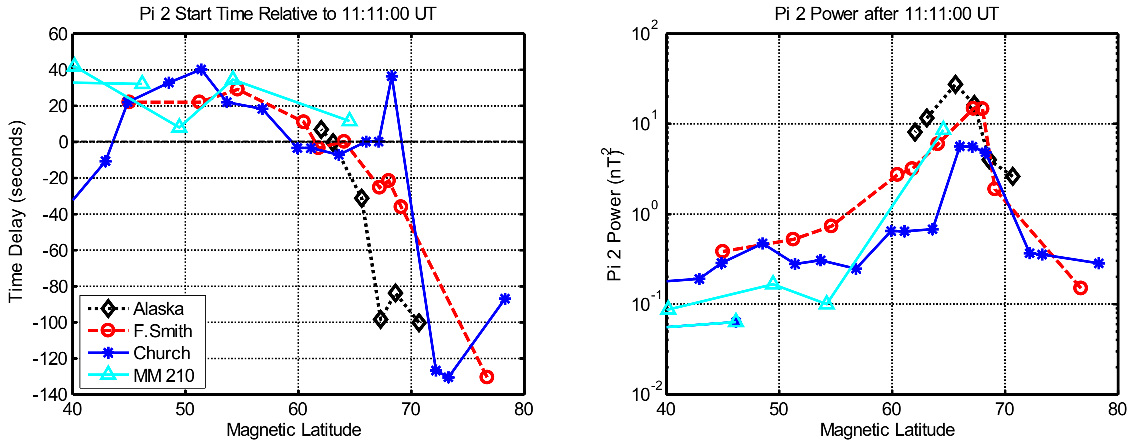

Figure 3. Left panel shows delay in Pi 2 onset times along the Churchill (blue *), Fort Smith (red o), Alaska (black diamond), and 210 Meridian (cyan triangle) arrays relative to 11:11:00 UT. Auroral zone onset time is ~11:10:30 UT. Right panel displays average Pi 2 band power in 5 minutes after onset versus magnetic latitude along the same four arrays. The signal is strongest in the North American auroral zone and decreases in strength from west to east. The onset is earliest in the west and latest in the east.