Substorm onset observations by IMAGE-FUV

H. U. Frey, S. B. Mende, and V. Angelopoulos
Space Sciences Laboratory, University of California, Berkeley, California, USA

E. F. Donovan
Department of Physics and Astronomy, University of Calgary, Calgary, Alberta, Canada

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[1] Over the first 2.5 years of operation, the FUV instrument on the IMAGE spacecraft observed more than 2400 substorm onsets in the Northern Hemisphere. The observations confirm earlier results of statistical studies in terms of a median substorm onset location at 2300 hours MLT and 66.4 degrees magnetic latitude. The purpose of this report is to publish the list to allow for further investigation. The list can easily be searched for onsets close to certain ground stations or at specific magnetic latitudes or local times. As one example of such use, we demonstrate how the probability of onset observation was determined for the ground-based automatic observatories of the THEMIS (Time History of Events and Macroscale Interactions during Substorms) project. *INDEX TERMS:* 2704 Magnetospheric Physics: Auroral phenomena (2407); 2788 Magnetospheric Physics: Storms and substorms; 2794 Magnetospheric Physics: Instruments and techniques; 2407 Ionosphere: Auroral ionosphere (2704); *KEYWORDS:* substorm onset, location, global distribution, THEMIS

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1. Introduction

[2] Substorms are the most violent and obvious signatures of the coupling between the magnetosphere and the ionosphere. They suddenly release hundreds of GW of power, create intense plasma flows in the plasma sheet, build up strong field-aligned currents, excite almost all kinds of electromagnetic waves, and cause strong energetic particle precipitation that create bright and dynamic auroras. They are still the topic of intense discussion and research with seven International Substorm Conferences held by the spring of 2004. The development of substorms is pretty well described by the traditional picture of growth, onset, expansion, and recovery phases [*Akasofu*, 1964; *McPherron*, 1972]. The two most common substorm theories propose different onset locations in the magnetotail and a different sequence of events. The Current Disruption Model puts the onset location near Earth (<8 R_e) with a current disruption that is quickly followed by the auroral breakup [*Lui et al.*, 1990, 1991; *Birn et al.*, 1999]. The Near-Earth Neutral Line Model [*Hones*, 1979] places the substorm initiation at $\approx$15–25 R_e and the auroral breakup occurs later than in the Current Disruption Model when the fast flows break near the Earth [*Shiokawa et al.*, 1998b]. However, the details of why, how, when, and where substorms start are still topics of intense research.

[3] Many scientific papers about substorm research with in situ measurements from spacecraft or ionospheric radars are event studies [see, e.g., *Baker et al.*, 1990; *Shiokawa et al.*, 1998a; *Ohtani et al.*, 2002; *Mende et al.*, 2003a; *Bristow et al.*, 2003]. The development of large systems of ground-based magnetometers or riometers, like MIRACLE or CANOPUS [*Amm et al.*, 2001; *Tanskanen et al.*, 2002; *Samson et al.*, 1992; *Voronkov et al.*, 1999; *Syrjäsuo*, 1998], allowed for more systematic studies of the magnetic pulsations and absorption features that are related to the substorm phases. The disadvantage of such systems is their Earth-bound rotational motion in local time. That motion keeps them in a favorable location at the average substorm onset location for only 4 hours around midnight. Nevertheless, there have been many successful statistical studies with ground-based instrumentation that created the basic knowledge about the substorm phases and the average onset locations [see, e.g., *Driatsky and Shumilov*, 1972; *Berkey et al.*, 1974]. On the other hand, it was only the development of space-based imagers that allowed for the determination of the global context for more systematic studies of the aurora component of substorms [*Akasofu*, 1974]. They allowed for studies related to an external or internal triggering of the substorm onset [see, e.g., *Lyons*, 1996; *Zhou and Tsurutani*, 2001; *Hsu and McPherron*, 2003]. They also provided the relative position of in situ measurements with regard to the onset location [see, e.g., [*Mende et al.*, 2003a]. The latest extensive study of seasonal and interplanetary magnetic field (IMF) effects on substorm onsets used 648 Polar UVI observations [*Liou et al.*, 2001]. The authors found systematic changes of lower onset latitude for $B_x > 0$ or $B_z < 0$ and increased latitudes for $B_x < 0$ or $B_z > 0$. They also found a $\approx$1 hour difference in the local time of onset between summer and winter season. All their observations happened in 1996–1997 shortly after the minimum of the past solar cycle.

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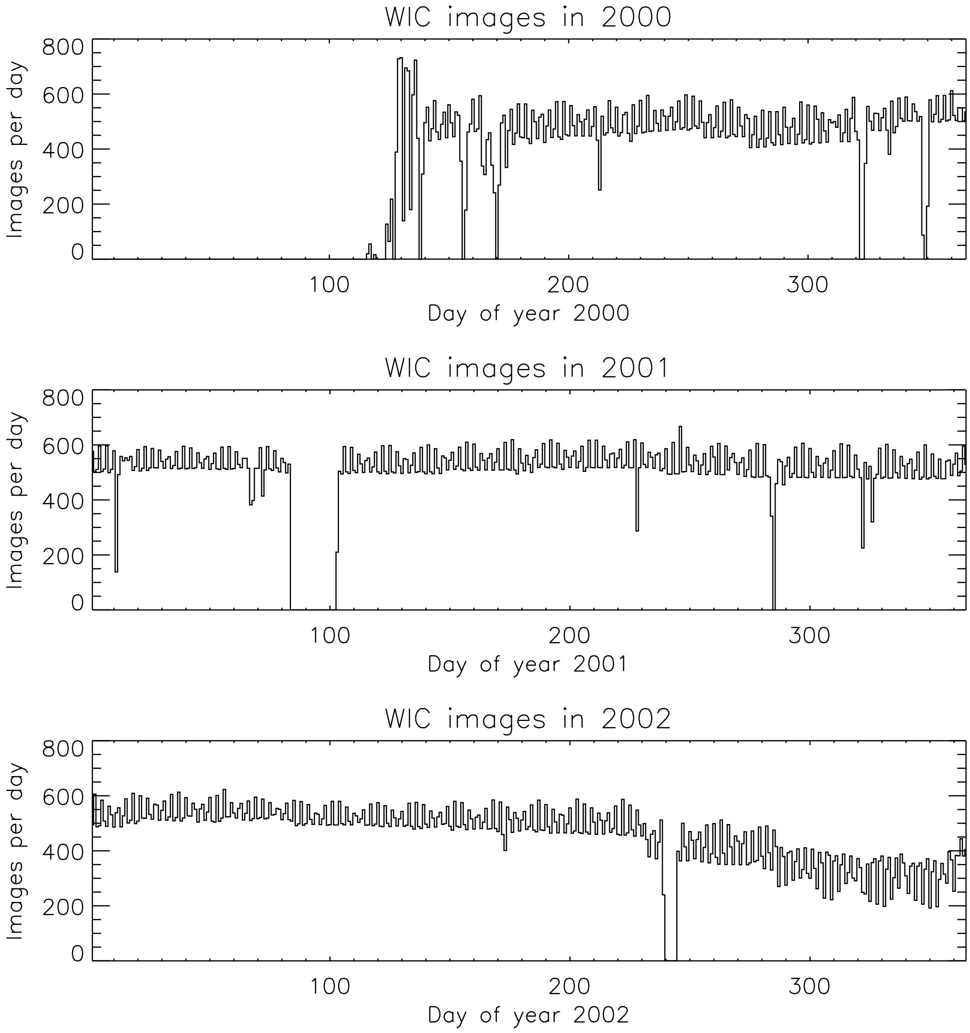

Figure 1. Summary of the total of WIC images that were recorded every day during the first 2.5 years of IMAGE-FUV operations.

[4] The FUV imager on the IMAGE spacecraft was designed to observe the aurora in ultraviolet light on a global scale with sufficient spatial and temporal resolution within the spacecraft telemetry limits. Over the first 2.5 years of operation in orbit it collected a vast amount of images of the northern auroral oval. Small subsets of these images were used to study the behavior of the proton aurora with respect to the usually observed electron excited aurora. The analysis of 78 winter substorms did not find any significant difference in the spatial distribution of the proton and electron onsets [*Gérard et al.*, 2004]. Another analysis of 91 substorms has established that there are differences in the expansion of the electron and proton precipitation after onset [*Mende et al.*, 2003b].

[5] For this report the full data set of FUV images was analyzed to identify substorm onsets in time and location and provide a list to the scientific community that can be used for further research. The observations between May 2000 and December 2002 cover the peak of the past solar cycle and coincide in time with the Cluster mission. This paper describes general properties of the data set and demonstrates its statistical significance. It also presents one example of how this data set was used to determine the probability of substorm onset observations by the planned Time History of Events and Macroscale Interactions during Substorms (THEMIS) ground station array.

2. Instrumentation

[6] The IMAGE satellite is in a highly elliptical polar orbit of 1000 × 45,600 km altitude. The Far Ultra-Violet imager (FUV) consists of three imaging subinstruments and observes the aurora for 5–10 s during every 2 min spin period [*Mende et al.*, 2000]. Major properties such as fields of view, spatial resolution, and spectral sensitivity were validated by in-flight calibrations with stars [*Frey et al.*, 2003]. The Wideband Imaging Camera (WIC) has a passband of 140–180 nm covering emissions from the N_2 LBH-band and atomic NI lines. The oxygen imaging Spectrographic Imager channel (SI-13) has a passband of 5 nm around the 135.6 nm doublet of oxygen OI emission. Both WIC and SI-13 observe what is traditionally considered as the "electron excited aurora," though there is excitation of the nitrogen and oxygen lines and bands not only from electrons but also from energetic protons that have to be considered for quantitative analyses [*Frey et al.*,

Table 1. Median and Mean (in Parentheses) Values of Auroral Substorm Onset From Several Statistical Studies (From *Liou et al.* [2001])

Satellite	Samples	MLT, hours	MLAT, degrees	References
DE-1	68	2250 (22.8)	65° (?)	*Craven and Frank* [1991]
Viking	133	2305 (22.8)	66.7° (65.8°)	*Henderson and Murphree* [1995]
Polar	648	2230 (22.7)	67° (66.6°)	*Liou et al.* [2001]
IMAGE (winter)	78	2324	65.6°	*Gérard et al.* [2004]
IMAGE	2437	2300 (23.0)	66.4° (66.1°)	Present paper

2003]. The SI-12 channel observes the proton aurora but is not used in this study. The WIC offers the best spatial resolution with a pixel size from apogee of 50 km, while the pixel size of SI-13 is 100 km from apogee.

[7] FUV is mounted on the spinning IMAGE satellite, and there are certain issues with the accuracy of the pointing information in the spin plane. The pointing is regularly corrected with bright UV stars that cross through the field of view. However, the final pointing error in the spin plane can be up to 4 pixels, while the one perpendicular to the spin plane can be up to 2 pixels. With the orbit that is fixed in inertial space, the larger uncertainties for the substorm onset determination are in the local time direction in summer and winter and in the latitude direction in spring and fall.

[8] The orbital period of IMAGE is 1414 hours. Apogee during the study period was over the Northern Hemisphere; perigee was in the south. The FUV imager is turned off during the passage through the radiation belt. That operation scheme allows for 8–10 hours of good observation conditions for the northern auroral oval during each orbit.

[9] Within the first 2.5 years of IMAGE-FUV operations, a total of 461,429 WIC images were collected. Figure 1 shows how many images were recorded every day. Not all of these images were useful for this investigation though, as the figure does not indicate how many of these images were showing the nightside auroras in the Northern Hemisphere. Several of these images were obtained in the Southern Hemisphere, while pointing to stars, while pointing to the equatorial airglow, or without high voltage. However, the figure indicates the periods when FUV was not operating and therefore no substorm identification was possible, for instance between 24 March and 13 April 2001.

3. FUV Observations

[10] During the time period of 19 May 2000 (start of regular IMAGE-FUV operations) to 31 December 2002 we searched through the FUV data and determined substorm onsets. The prime data source were the WIC images because of their better spatial resolution. During times when WIC did not provide the best view of the aurora, SI-13 images were used instead. Substorms were identified if they fulfilled the following criteria: (1) a clear local brightening of the aurora has to occur, (2) the aurora has to expand to the poleward boundary of the auroral oval and spread azimuthally in local time for at least 20 min, (3) a substorm onset was only accepted as a separate event if at least 30 min had passed after the previous onset.

[11] The third criterion eliminated several closely spaced onsets or "multionset substorms." Criterion 2 eliminated pseudobreakups that did not develop into full substorms. Within the image of the initial auroral brightening, the center of the substorm aurora was first determined visually. Then a computer program determined the brightest pixel close to this location and calculated its geographic and geomagnetic locations. The full data set is available as an

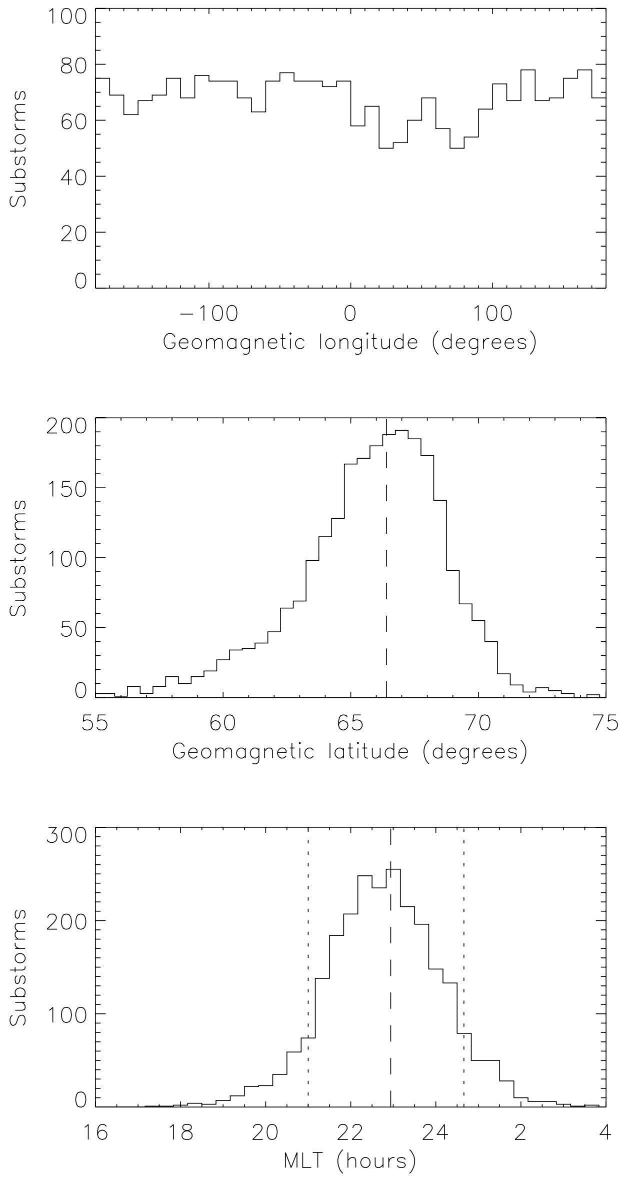

Figure 2. Histograms of the distribution of substorm onsets in geomagnetic longitude (top), latitude (middle), and local time (bottom). The median values are marked in the two bottom panels. The last panel also shows the range in local time with more than 80% of observed substorms (10% on each side).

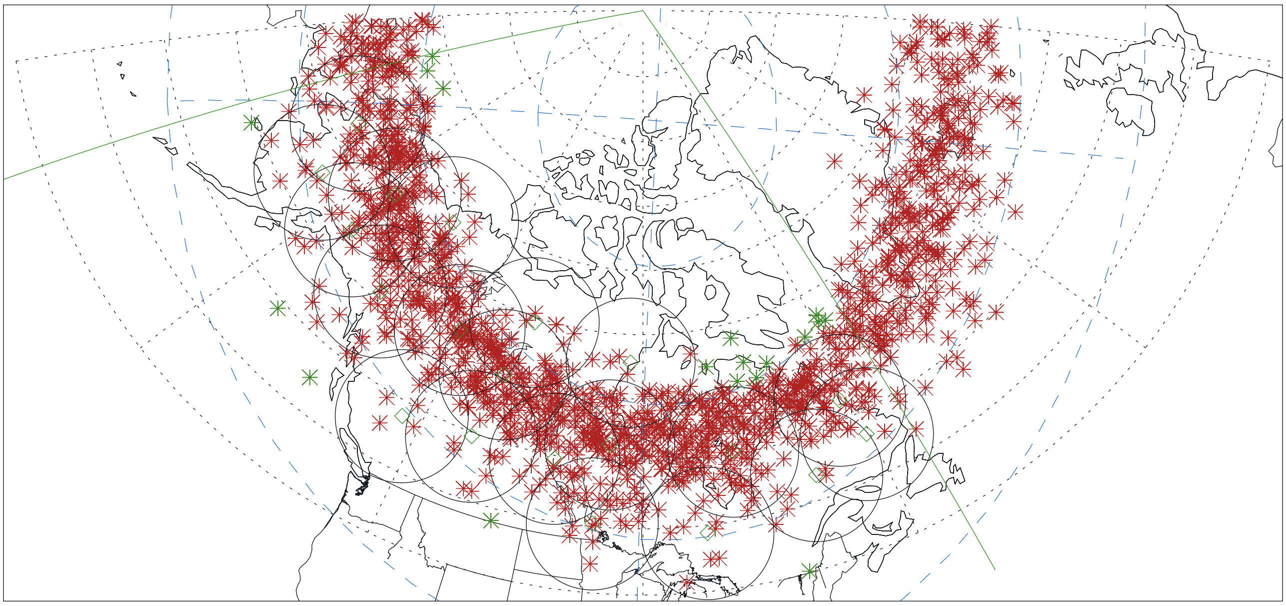

Figure 3. Map of North America showing the substorm onset locations in geographic coordinates regardless of the local time of onset. A geomagnetic grid is given in blue. The presently planned locations of the THEMIS GBO are indicated with the fields of view of their all-sky cameras. Ninety-eight percent of the substorms started within 600 km to the closest planned GBO. Each substorm onset location is given with a red asterisk. Those onsets outside of the field of view of the THEMIS all-sky cameras are marked with green asterisks.

electronic supplement[1] to this paper, and other scientists are invited to use the data for their research. The list contains the date and time of each substorm onset, which FUV instrument was used for the identification (WIC or SI-13), the spacecraft geocentric distance, and the brightness (instrument counts) and location (x/y pixel, geographic, and geomagnetic) of the brightest pixel within the onset surge. The list can easily be searched for specific criteria like onsets at high magnetic latitude, late local time, onsets within a certain distance to a particular ground station, or onsets with a small distance to the IMAGE spacecraft promising better spatial resolution.

[12] The averaged results for the substorm onsets confirm results of earlier studies, for instance with DE-1 [*Craven and Frank*, 1991], Viking [*Henderson and Murphree*, 1995], and Polar-UVI [*Liou et al.*, 2001]. We reproduce here Table 1 from *Liou et al.* [2001] and add the results of an analysis of a very small subset of FUV observations [*Gérard et al.*, 2004] and our results for comparison. Figure 2 summarizes the onset locations in geomagnetic longitude, latitude, and local time. Substorm onsets are evenly distributed in magnetic longitude, and there is no bias in this data set toward specific locations. The shapes of the distributions closely resemble those from earlier studies [*Liou et al.*, 2001].

4. Discussion

[13] The list of substorms was used to analyze the locations of ground-based observatories (GBO) that will be fielded in North America for the THEMIS (Time History of Events and Macroscale Interactions during Substorms) project. THEMIS is a five- spacecraft mission that is scheduled for launch in fall 2006. The spacecraft will be in eccentric orbits with 10, 12, 12, 20, and 30 R_e apogees that will have conjunctions in the magnetotail every 4 days. The major goal of the mission is to resolve the mystery of where, when, and how auroral substorms start. In addition to the in situ measurements by the spacecraft, the mission success heavily depends on additional information from an array of 20 ground-based observatories (GBO). Each GBO will be equipped with a white-light all-sky camera. In addition to the all-sky cameras that could be compromised by thick cloud cover, the GBOs also have fluxgate magnetometers with 0.5 Hz temporal resolution. They will additionally determine the onset time through bursts of irregular magnetic pulsations (PiB) [*Boesinger et al.*, 1981] and Pi2 pulsations [*Liou et al.*, 1999; *Kepko et al.*, 2004]. The goal of these GBOs is to identify the auroral breakup of the substorm onset within 3–5 seconds.

[14] In addition to the THEMIS in situ spacecraft observations, it is extremely important to identify the timing of the auroral breakup with the best possible accuracy, to cover as much of an area with the smallest number of observatories, and to place the stations at locations that are most likely to be close to the breakup position. The list of substorm onsets was then the ideal tool to investigate the proposed locations for the GBOs in order to get a complete coverage and a decent amount of overlap of the fields of view of the all-sky cameras. Figure 3 shows the location of all substorm onsets in geographic locations, regardless of their local time.

[15] Out of the total of 2437 substorms in the FUV data, 1022 occurred in the area that will be covered by the THEMIS-GBO (190–305° geographic longitude). Of those substorms only 2% would not fall into the field of view of the planned all-sky cameras because they started at a

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/ja/2004JA010607.

distance larger than 600 km to the closest all-sky camera. The geomagnetic latitude lines in Figure 3 at 60° and 70° bracket the latitude where more than 91% of the substorms occurred, and that region will be covered by the overlapping all-sky camera fields of view.

5. Summary

[16] The data of more than 2400 substorm onset locations between May 2000 and December 2002 confirm previous findings of average distributions in geomagnetic latitude and local time. The data set is not biased toward any specific geomagnetic longitude locations as is expected for long-term observations from a satellite in a nonlocked orbit with a period that is not a multiple of the Earth rotational period.

[17] The prime purpose of this report is to publish the list of FUV substorm observations. Files summarizing all substorm onsets used for this study are available as an electronic supplement.[1] Other researchers are invited to look at those time periods with their data and different instrumentation. The database can easily be searched for specific criteria like onsets at high magnetic latitude, late local time, onsets within a certain distance to a particular ground station, or those with a small distance to the IMAGE spacecraft giving better spatial resolution.

[18] The list of substorm observations was used to investigate the probability of substorm onset observations for the THEMIS-GBO. It is expected that the GBOs will be capable to observe at least 98% of all substorms originating over North America. Weather permitting, these observations will primarily use the all-sky cameras, but even during overcast skies the ground-based magnetometers will be able to determine the onset time through the analysis of PiB and Pi2 pulsations.

[19] During almost all of the reported substorm onsets there exist also images of the proton aurora taken by the SI-12 channel on IMAGE. Previous analysis of small subsets of FUV images did not find any significant difference in the spatial distribution of the proton and electron onsets [*Gérard et al.*, 2004], but differences in the expansion of the electron and proton precipitation dominated auroras [*Mende et al.*, 2003]. Such investigation has not been performed for this study, and more statistically significant results could be obtained with a further analysis of the present data set.

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V. Angelopoulos, H. U. Frey, and S. B. Mende, Space Sciences Laboratory, University of California, Berkeley, CA 94720-7450, USA. (hfrey@ssl.berkeley.edu)

E. F. Donovan, Department of Physics and Astronomy, University of Calgary, Calgary, Alberta T2N 1N4, Canada. (eric@phys.ucalgary.ca)