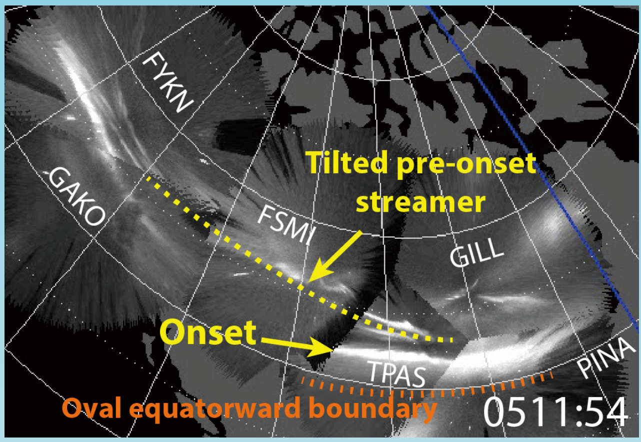
# Earth, Planets and Space

The 13th International Conference on Substorms





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**PREFACE** **Open Access**

# Special issue "The 13th International Conference on Substorms"

James LaBelle[1*], Marc Lessard[2], Masahito Nosé[3] and Joachim Raeder[2]

The Thirteenth International Conference on Substorms (ICS-13) was held September 25–29, 2017, in Portsmouth, New Hampshire, USA. The conference featured 64 oral scientific presentations, including 5 one-hour-long Socratic dialogs with broad participation, and 27 poster presentations. Approximately 100 scientists attended, including many students. Following the pattern established in previous conferences, participants were invited to submit papers inspired by the conference to a special issue of Earth, Planets and Space. The resulting papers span an impressive range of substorm-related topics as well as a range of techniques including modeling, ground- and space-based optical imaging, radioscience, satellite plasma measurements, and magnetometry.

Ieda et al. (2018) present an interesting highly time-resolved case study of a substorm onset observed simultaneously with ground-based and satellite-based optical instruments. The study reveals that brightening followed by polar motion seen in the satellite-based data coincides with brightening and poleward expansion in the ground-based images but comes a few minutes after the "Akasofu initial brightening" seen in the ground-based data. The explanation remains uncertain, but may possibly be attributed to the limited spatial resolution of the satellite-based data. Potential implications for definition and identification of substorm onsets are discussed in the paper.

Lyons et al. (2018) examine sixty substorms occurring during eighteen geomagnetic storms, using the wide geographic coverage of the THEMIS all-sky imagers (ASIs). The data provide strong evidence of onsets triggered by plasma sheet flow bursts appearing as streamers in the optical aurora data. The data also give an opportunity to compare substorms during CME-generated geomagnetic storms versus those occurring during High-Speed Stream type storms, revealing interesting differences in the number and cadence of substorms during each type.

Spencer et al. (2018) use solar wind data from the ACE satellite together with a low-dimensional energy-conserving state space model for substorm dynamics of the nightside magnetosphere to predict AL index time series and other substorm indicator parameters. In seven case studies, the model reproduces substorm events both in approximate time duration and activity level, when compared with actual AL or SML data.

Liang et al. (2018) examine optical imaging data during twelve substorms, focusing on the spectroscopic lines characteristic of proton precipitation during the late growth stage feature called the "transitional stage to substorm onset" in which the electron-excited emissions intensify and beading occurs along the optical arc form. Surprisingly, in contrast to the electron emissions, the proton lines increase minimally during this transitional stage and only increase strongly afterward. Liang et al. (2018) show that the muted proton aurora effect cannot be completely explained by, for example, spatial spreading of the proton auroras. It may have important implications for explaining late growth phase and onset phenomena such as TSSO.

Antonova et al. (2018) explore the relationship between substorms and variations in outer radiation belt electrons, both statistically and by consideration of adiabatic acceleration of electrons in the relaxing magnetic field in the wake of the substorm. They put forth that the substorms occurring in the storm recovery phase are of particular importance for affecting trapped particle populations.

Vorobjev et al. (2018) investigate a large number of isolated substorms, finding an unexpected relationship between their intensity and the solar wind dynamic

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pressure (unexpected because the usual energy coupling parameters do not depend strongly on dynamic pressure). While interpretation is uncertain, they show evidence that the dynamic pressure is correlated with energy coupling parameters during the late growth phase of substorms, and they put forth that the enhanced coupling creates conditions leading to the subsequent substorm being more intense.

Two papers focus attention on the famous "Saint Patrick's Day Storm" of 2015. Kozyreva et al. (2018) illustrate new tools and techniques by applying them to the many substorm-like disturbances that occurred during the lengthy recovery phase of the Saint Patrick's Day Storm. They develop a virtual magnetogram technique similar to that employed by, for example, the SuperMag facility, and including consideration of localized geomagnetic variations dB/dt. The case study shows evidence suggesting differences in locations of the variations versus the canonical onset location which may have implications for predicting geomagnetically induced currents.

Suji and Prince (2018) also investigate the Saint Patrick's Day storm, combining observations and modeling to independently estimate the local Joule heating and the global Joule heating during each of five substorms occurring during the storm main and recovery phases. Local Joule heating is only a small fraction of global Joule heating for the substorms occurring during main phase but a large fraction of global Joule heating for those during recovery phase. The authors put forth the possible explanation that during storm main phase, there are several pathways whereby energy may be deposited into the ionosphere, and hence the proportion of global Joule heating associated with the substorm during main phase is small, whereas during storm recovery phase, when the system is no longer being strongly externally driven, piled up magnetic flux in the tail is redistributed between dayside and nightside via substorms, and hence the proportion of global Joule heating associated with the recovery phase is large.

Finally, LaBelle (2018) probes a natural auroral radio emission, called medium frequency burst (MFB), which characterizes substorm onsets and has potential to serve for timing or location of onsets. The cause of these emissions has not been established but is believed to be related to Langmuir wave excitation. MFB occurs primarily at frequencies of several MHz, well above the electron gyrofrequency, but an outstanding mystery is the nature of occasional occurrences below the gyrofrequency, previously speculated to be whistler mode. LaBelle (2018) presents the first measurements of the polarization of these low-frequency MFB emissions, showing them to be left-polarized and hence LO-mode not whistler mode. The observation places constraints on the source altitude of the emissions.

These nine papers herald advances in a variety of aspects of auroral substorms, and they provide the basis for better understanding of polar substorms and the underlying ionospheric and magnetospheric processes.

**Abbreviations**

ACE: advanced composition explorer; AL: amplitude lower; ASI: all-sky imager; CME: coronal mass ejection; ICS: international conference on substorms; LO: left/ordinary polarization; MFB: medium frequency burst; SML: super mag lower; THEMIS: time history of events and macroscale interactions during substorms; TSSO: transitional stage to substorm onset.

**Authors' contributions**

All authors of this article served as the guest editors for this special issue. JL prepared this preface with the agreement of the other authors. All authors read and approved the final manuscript.

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**Competing interests**

The authors declare that they have no competing interests.

**Availability of data and materials**

The only data of this preface are the articles comprising this special issue published in Earth, Planets and Space.

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**Ethics approval and consent to participate**

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# Simultaneous observation of auroral substorm onset in Polar satellite global images and ground-based all-sky images

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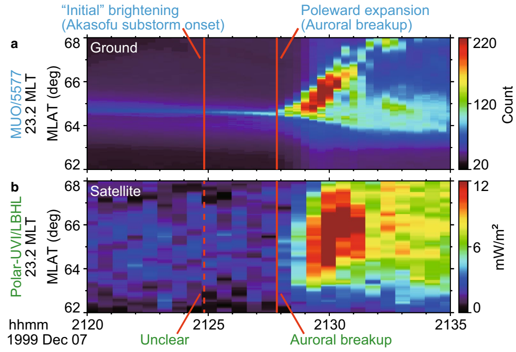
## Abstract

Substorm onset has originally been defined as a longitudinally extended sudden auroral brightening (Akasofu initial brightening: AIB) followed a few minutes later by an auroral poleward expansion in ground-based all-sky images (ASIs). In contrast, such clearly marked two-stage development has not been evident in satellite-based global images (GIs). Instead, substorm onsets have been identified as localized sudden brightenings that expand immediately poleward. To resolve these differences, optical substorm onset signatures in GIs and ASIs are compared in this study for a substorm that occurred on December 7, 1999. For this substorm, the Polar satellite ultraviolet global imager was operated with a fixed-filter (170 nm) mode, enabling a higher time resolution (37 s) than usual to resolve the possible two-stage development. These data were compared with 20-s resolution green-line (557.7 nm) ASIs at Muonio in Finland. The ASIs revealed the AIB at 2124:50 UT and the subsequent poleward expansion at 2127:50 UT, whereas the GIs revealed only an onset brightening that started at 2127:49 UT. Thus, the onset in the GIs was delayed relative to the AIB and in fact agreed with the poleward expansion in the ASIs. The fact that the AIB was not evident in the GIs may be attributed to the limited spatial resolution of GIs for thin auroral arc brightenings. The implications of these results for the definition of substorm onset are discussed herein.

**Keywords:** Substorm, Auroral breakup, Aurora, Substorm onset, Global images, All-sky images




Graphical abstract

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# Stormtime substorm onsets: occurrence and flow channel triggering

Larry R. Lyons*, Ying Zou, Yukitoshi Nishimura, Bea Gallardo-Lacourt, Vassilis Angelopulos and Eric F. Donovan

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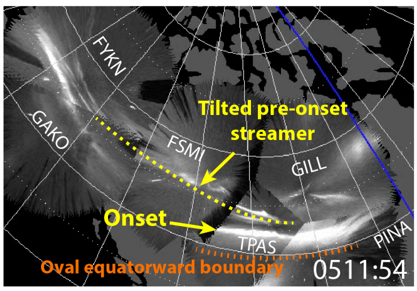
## Abstract

Bright auroral emissions during geomagnetic storms provide a good opportunity for testing the proposal that substorm onset is frequently triggered by plasma sheet flow bursts that are manifested in the ionosphere as auroral streamers. We have used the broad coverage of the ionospheric mapping of the plasma sheet offered by the high-resolution THEMIS all-sky-imagers (ASIs) and chose the main phases of 9 coronal mass ejection (CME) related and 9 high-speed stream (HSS)-related geomagnetic storms, and identified substorm auroral onsets defined as brightening followed by poleward expansion. We found a detectable streamer heading to near the substorm onset location for all 60 onsets that we identified and were observed well by the ASIs. This indicates that substorm onsets are very often triggered by the intrusion of plasma with lower entropy than the surrounding plasma to the onset region, with the caveat that the ASIs do not give a direct measure of the intruding plasma. The majority of the triggering streamers are "tilted streamers," which extend eastward as their eastern tip tilts equatorward to near the substorm onset location. Fourteen of the 60 cases were identified as "Harang streamers," where the streamer discernibly turns toward the west poleward of reaching to near the onset latitude, indicating flow around the Harang reversal. Using the ASI observations, we observed substantially less substorm onsets for CME storms than for HSS storms, a result in disagreement with a recent finding of approximately equal substorm occurrences. We suggest that this difference is a result of strong non-substorm streamers that give substorm-like signatures in ground magnetic field observations but are not substorms based on their auroral signature. Our results from CME storms with steady, strong southward IMF are not consistent with the ~2–4 h repetition of substorms that has been suggested for moderate to strong southward IMF conditions. Instead, our results indicate substantially lower substorm occurrence during such steady driving conditions. Our results also show the much more frequent occurrence of substorms during HSS period, which is likely due to the highly fluctuating IMF.

**Keywords:** Substorms, Storms, Auroral streamers, Substorm triggering, Substorm occurrence

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# The dynamics of geomagnetic substorms with the WINDMI model

Edmund Spencer*, Sai Krishna Vadepu, Pavithra Srinivas, Swadesh Patra and Wendell Horton

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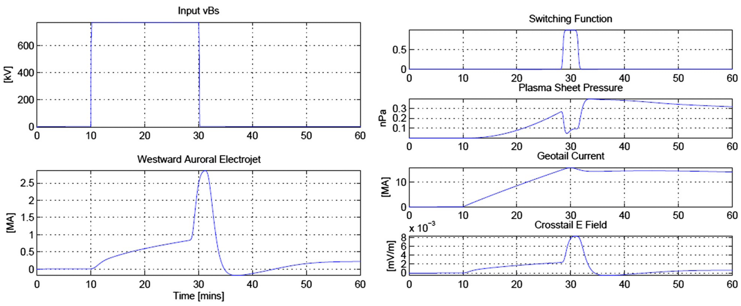
## Abstract

The global dynamics of substorms are controlled by several key magnetospheric parameters. In this work we obtain quantitative measures of these parameters from a low-order nonlinear model of the nightside magnetosphere called WINDMI. The model uses solar wind and IMF measurements from the ACE spacecraft as input into a system of 8 nonlinear ordinary differential equations. The state variables of the differential equations represent the energy stored in the geomagnetic tail, central plasma sheet, ring current and field-aligned currents. The output from the model is the geomagnetic westward auroral electrojet (AL) index and the Dst index. Intermediate variables of the model are the plasma sheet pressure, geotail current, cross-tail electric field, parallel ion velocity and the pressure gradient current. The values of these variables are controlled by physical parameters of the model, consisting of spatially averaged quantities that are analogous to electric circuit elements. We tune the model to re-produce substorm events, comparing model capability against observations of auroral brightening and the auroral electrojet indices AL from WDC Kyoto and SML from SuperMAG. The model is capable of capturing events within a 10–12-min interval of occurrence, with level of activity comparable to the measured indices.


**Keywords:** WINDMI, Magnetosphere, Substorm




Graphical abstract

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# Proton auroras during the transitional stage of substorm onset

Jun Liang*, Eric Donovan, Deborah Gillies, Emma Spanswick and Martin Connors

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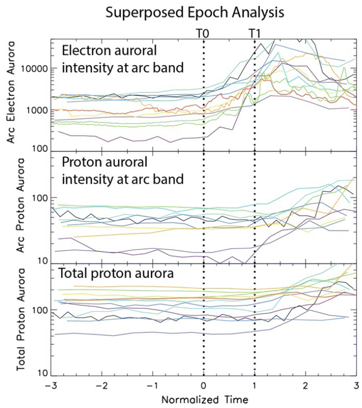
## Abstract

Optical auroral measurements repeatedly reveal the existence of a transitional stage between a quiescent preexisting arc and its significant auroral expansion in a substorm onset. Such a transitional stage of substorm onset (TSSO) is characterized by a gradual intensification and the emergence of auroral beads, along the preexisting arc. However, existing studies on TSSO are limited to electron auroras which are dominant in optical luminosity. In this study, we collect 12 substorm events to investigate the proton auroral features during the late growth phase and the TSSO. Our major results include: (1) we confirm the previous notion that the onset electron auroral arc is usually located at the poleward "shoulder" of the main proton auroral band. (2) While the electron auroral arc typically intensifies by a few times or even an order of magnitude during the TSSO, the concurrent proton aurora at the same location as the electron auroral arc shows much less noticeable variations. The proton auroral variations averaged over the arc band, as well as that integrated over the entire latitudinal range, are mostly within 10% of their mean late-growth-phase levels during the TSSO. Substantial intensifications of proton auroras occur after the poleward expansion of electron auroras. Even considering the spatial spreading of proton auroras, we estimate that the variation of ion precipitation fluxes on top of the ionosphere would be typically < 30% during the TSSO. The above observations impose implications and quantitative constraints on the possible mechanisms of TSSO and substorm onset. We assert that there is no significant ion energization or large-scale magnetic field reconfiguration during the TSSO. Instead, it is likely that the underlying mechanism of the TSSO might be certain kind of ky-dominated instability wave mode. The instability wavelength is comparable to the ion gyroradius, so that the ions are demagnetized, suppressing ion flux variations with the instability. Enhancing upward electric fields in the auroral acceleration region during the TSSO may also play a partial role in weakening the ion precipitation flux variation.


**Keywords:** Auroral substorm, Transition stage of substorm onset, Proton aurora, Electron aurora, Preexisting auroral arc, Nightside transition region




Graphical abstract

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**FULL PAPER** **Open Access**

# Processes in auroral oval and outer electron radiation belt

Elizaveta E. Antonova*, Marina V. Stepanova, Pablo S. Moya, Victor A. Pinto, Vadim V. Vovchenko, Ilya L. Ovchinnikov and Nikita V. Sotnikov

*Earth, Planets and Space* 2018, **70**:127 DOI: 10.1186/s40623-018-0898-1
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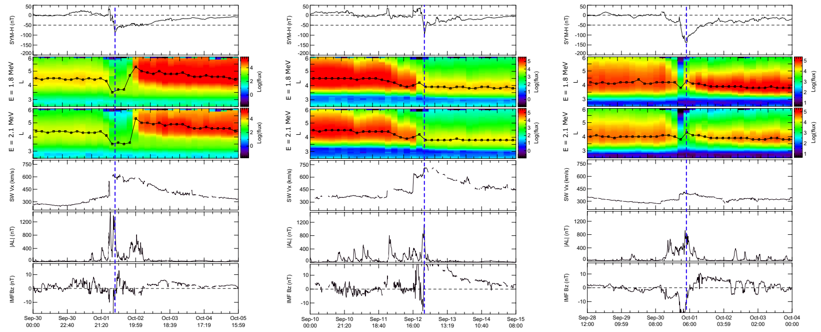
## Abstract

We have analyzed the role of auroral processes in the formation of the outer radiation belt, considering that the main part of the auroral oval maps to the outer part of the ring current, instead of the plasma sheet as is commonly postulated. In this approach, the outer ring current is the region where transverse magnetospheric currents close inside the magnetosphere. Specifically, we analyzed the role of magnetospheric substorms in the appearance of relativistic electrons in the outer radiation belt. We present experimental evidence that the presence of substorms during a geomagnetic storm recovery phase is, in fact, very important for the appearance of a new radiation belt during this phase. We discuss the possible role of adiabatic acceleration of relativistic electrons during storm recovery phase and show that this mechanism may accelerate the relativistic electrons by more than one order of magnitude.

**Keywords:** Magnetospheric storm and substorm, Auroral oval, Acceleration of electrons of the outer electron radiation belt



The 1 October 2013 geomagnetic storms when the increase of outer radiation belt fluxes is observed.

The12 September 2014 geomagnetic storm, when the decrease of outer radiation belt fluxes is observed.

The 30 September 2012 geomagnetic storm, when outer radiation belt fluxes after storm were nearly the same as before the storm.

Graphical abstract

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**FULL PAPER** **Open Access**

# Polarization measurements of unusual cases of medium frequency burst emissions extending below 1.5 MHz

J. LaBelle

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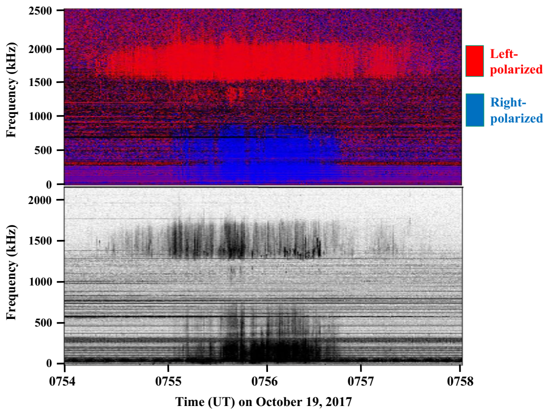
## Abstract

Auroral medium frequency burst (MFB) is a radio emission of natural auroral origin associated with substorm expansion phase and observable at ground level. The emission usually occurs at frequencies above 1500 kHz, but occasionally it extends to a sharp lower cutoff frequency at 1300–1500 kHz depending on the observing site, with a frequency gap below the cutoff and sporadic emission below the gap extending to frequencies as low as 1000 kHz. These low-frequency MFB components lie below the electron gyrofrequency and hence could represent either whistler or LO-modes. Recently, using crossed antennas and a two-channel receiver at Toolik Lake, Alaska, polarization of these low-frequency MFB components was measured for the first time and found to be left-hand. This observation eliminates whistler mode as a possibility and requires the low-frequency components be LO-mode in the ionosphere, which constrains their source location since it requires that the frequency exceeds the L-cutoff frequency. In these occasional events marked by a cutoff and low-frequency MFB components, the latter probably originate at high altitudes (>800 km) and reach the ground through extraordinary low-density polar cap ionosphere.

**Keywords:** Auroral radio emission, Substorm, Substorm onset, Langmuir wave, Mode conversion radiation, Medium frequency burst

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**FULL PAPER** **Open Access**

# How the intensity of isolated substorms is controlled by the solar wind parameters

Vyacheslav Georgievich Vorobjev*, Elizaveta Evgenievna Antonova and Oksana Ivanovna Yagodkina

*Earth, Planets and Space* 2018, **70**:148 DOI: 10.1186/s40623-018-0922-5
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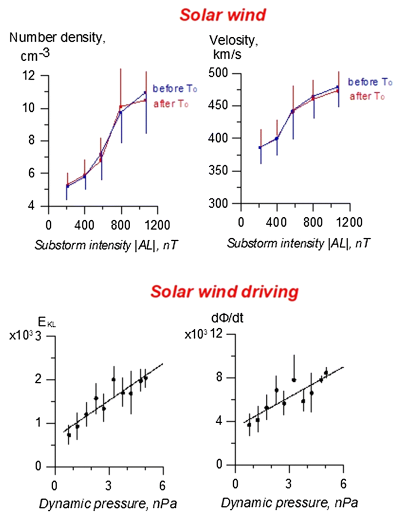
## Abstract

Analysis of 163 isolated substorms showed that their intensity quantified as a maximum absolute value of the AL index increases with an increase in the velocity and number density of the solar wind plasma and hence its dynamic pressure. Most of the coupling functions describing the energy loading to the magnetosphere, e.g., the Kan–Lee electric field ($E_{KL}$) and the Newell factor ($d\Phi/dt$), do not include the dynamic pressure as an input parameter. Having examined the correlation between these functions and the dynamic pressure, we found that, surprisingly, while almost uncorrelated for any arbitrary time interval, both $E_{KL}$ and $d\Phi/dt$ correlate with the dynamic pressure within 1 h before the onset of isolated substorms. That is, an increase in the solar wind dynamic pressure is associated with an increase in the solar wind driving before the onset. We assume that the increase in the dynamic pressure as early as before substorm growth path creates the conditions inside the magnetosphere that impede the occurrence of substorms and increase the threshold for the instability leading to expansion onset, forcing the accumulation of greater amount of energy in the magnetosphere. This energy is released during substorm expansion, producing a more intense magnetic bay.

**Keywords:** Isolated substorms, Substorm onset, The AL index, Solar wind plasma, Solar wind driving



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**FULL PAPER** **Open Access**

# Ground geomagnetic field and GIC response to March 17, 2015, storm

Olga V. Kozyreva, Vyacheslav A. Pilipenko*, Vladimir B. Belakhovsky and Yaroslav A. Sakharov

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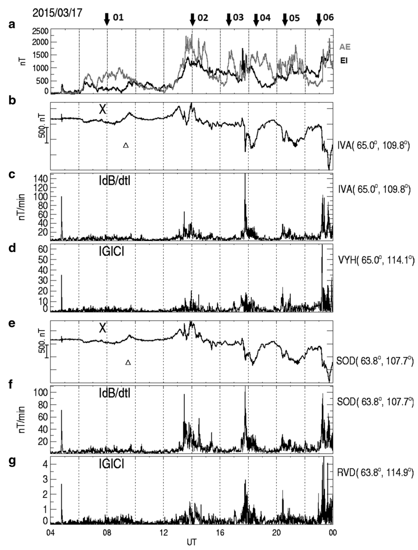
## Abstract

The St. Patrick's Day geomagnetic storm on March 17, 2015, has been chosen by the space community for synergetic analysis to build a more comprehensive picture of the storm's origin and evolution. This storm had an unusually long (~ 17 h) main phase. During this period, many substorm-like activations occurred. These activations resulted in bursts of geomagnetically induced currents (GICs) in power lines on the Kola peninsula. To examine the substorm activations in more detail, we apply various data processing techniques for the world-wide array of magnetometers: the virtual magnetograms, magnetic latitude–local time (MLT) snapshots, and magnetic keograms. These techniques are simple tools that are supplementary to more advanced facilities developed for the analysis of SuperDARN, IMAGE, and CARISMA arrays. We compare the global spatial localization and time evolution of the geomagnetic *X*-component disturbance and magnetic field variability measured by the Hilbert transform of time derivative $d\mathbf{B}/dt$. The latitude-MLT mapping of these magnitudes shows that very often a region with highest magnetic variability does not overlap with a substorm "epicenter" but is shifted to its poleward or equatorward boundaries. Highest variability of the geomagnetic field, and consequently intense GICs, are caused by medium-scale fast varying structures. There is no one-to-one correspondence between substorm intensity and GIC magnitude.

**Keywords:** Geomagnetic storm, Substorm, Geomagnetically induced currents, Virtual magnetometer



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# Global and local Joule heating during substorms in St. Patrick's Day 2015 geomagnetic storm

K. J. Suji and P. R. Prince*

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## Abstract

The first super storm of solar cycle 24 occurred on "St. Patrick's Day" (17 March 2015), with a minimum Dst level of – 223 nT. Five major substorms in this super storm were selected, with minimum values of local electrojet index (IL) ranging from – 1662 to – 673 nT. The selected substorms are all in the 22:00 MLT–06:00 MLT sector of the auroral oval region showing associated Pi2s and negative bays in the H-component of magnetograms, derived from the IMAGE magnetometer longitudinal (Fennoscandia) chain. The solar wind energy input is estimated as time integral of Akasofu's epsilon parameter, determined from the SuperMAG magnetometer. The local ionospheric Joule heating (local JH) rate, in the midnight or post-midnight sectors, is estimated using a modified form of Ahn's empirical conversion. The Global ionospheric Joule heating rate in the northern hemisphere (global JH) is taken from OpenGGCM model. For the substorm in the main phase of the superstorm, the local JH consumes only 9% (8%, if the IL is replaced by AL index in the empirical conversion relation) of the global JH. However, 40–86% (39–48%, if the IL is replaced by AL index in the empirical conversion relation) of global JH is consumed as local JH for the remaining substorms.

**Keywords:** Geomagnetic storms, Substorms, Pi2 pulsations, Ionospheric Joule heating

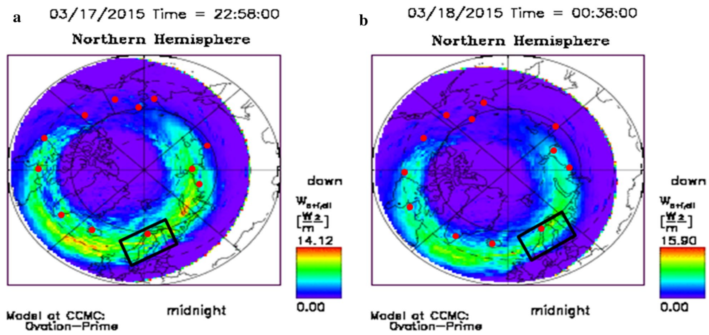


Fig. 3

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# Contents



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