Geospace system responses to the St. Patrick's Day storms in 2013 and 2015

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Special Section:
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Key Points:
- A collection of 31 papers covering observational and modeling aspects for 2015 and 2013 St. Patrick's Day storms
- Broad geospace storm topics, with some emphasis on the ionosphere-thermosphere system and its coupling to the magnetosphere
- We provide highlights of the studies that reveal a big picture of the storm time geospace dynamics; we discuss areas of future challenges

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Geospace system responses to the St. Patrick's Day storms in 2013 and 2015

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Abstract This special collection includes 31 research papers investigating geospace system responses to the geomagnetic storms during the St. Patrick's Days of 17 March 2013 and 2015. It covers observation, data assimilation, and modeling aspects of the storm time phenomena and their associated physical processes. The ionosphere and thermosphere as well as their coupling to the magnetosphere are clearly the main subject areas addressed. This collection provides a comprehensive picture of the geospace response to these two major storms. We provide some highlights of these studies in six specific areas: (1) global and magnetosphere/plasmasphere perspectives, (2) high-latitude responses, (3) subauroral and midlatitude processes, (4) effects of prompt penetration electric fields and disturbance dynamo electric fields, (5) effects of neutral dynamics and perturbation, and (6) storm effects on plasma bubbles and irregularities. We also discuss areas of future challenges and the ways to move forward in advancing our understanding of the geospace storm time behavior and space weather effects.

Plain Language Summary This paper provides an introduction to the JGR-Space Physics special collection on "Geospace system responses to the St. Patrick's Day storms in 2013 and 2015." It summaries the main results of each paper in the collection which form a comprehensive picture of the geospace response to these two major storms. It discusses also areas of future challenges and the ways to move forward in advancing our understanding of the geospace storm time behavior and space weather effects.

1. Introduction

With more than five decades of tireless and creative endeavors, our understanding of the geospace storm response has advanced to a systematic view. Storm time changes in the magnetosphere, ionosphere, and atmosphere are fundamentally dynamic, interactive, and nonlinear. These changes may be represented by variations in key parameters, such as electromagnetic field and currents, particle precipitation, neutral winds and composition, and ionospheric electron densities and total electron content. The essential physical processes as building blocks interconnecting the coupled system of the magnetosphere, ionosphere, and thermosphere are more or less in place (although to a certain degree some remain speculative or qualitative). However, their relative importance of them changes from case to case, yielding significantly different scenarios of the storm time geospace responses.

New discoveries are often triggered by new capabilities in observations and modeling. The major geomagnetic storms during 17–18 March in 2013 and 2015 provide us a fresh opportunity to examine which processes actually are working and their relative roles in causing geospace impacts. These storms can serve as an excellent test bed for current theories and concepts. The two events, especially the 2015 event being the strongest over the current solar cycle, have attracted much community attention. They have been the subject of a number of dedicated workshop and conference sessions, e.g., during the 2015 CEDAR workshop and 2015 Fall AGU meeting. In such a modern era where observations from ground-based and in situ sensors have become very extensive and global numerical models have been more advanced, it is appropriate and timely that a Journal Geophysical Research special collection focuses on characterizing and understanding storm time geospace behavior during these specific events. This special collection includes 31 papers written by researchers from around the world and covers geospace observation, data assimilation, and modeling aspects of the storm time interplanetary and magnetospheric characteristics; in particular, the ionosphere and thermosphere, as well as their coupling to the magnetosphere are the focus of many papers.

2. Main Results: Geospace Responses to the St. Patrick's Day Storms

1. *Global and magnetosphere/plasmasphere perspectives*. Geospace system-wide effects during the St. Patrick's Day storms are described in a number of papers. *Verkhoglyadova et al.* [2016] examined complex interplanetary structures during the storms of different intensities in March 2012, 2013, and 2015 of different intensities and found that different ionospheric and thermospheric (I/T) responses demonstrated both some strong and some less direct connection between external driving and I/T dynamics. Using cross-scale magnetospheric observations by Time History of Events and Macroscale Interactions (THEMIS), Van Allen Probes, and Two Wide-angle Imaging Neutral-atom Spectrometers (TWINS), *Goldstein et al.* [2016] showed spatial, spectral, and temporal variations of the storm time magnetosphere and plasmaspheric structures during the 2015 event, including magnetospheric compression and two-peak ion spectrum in the center of the partial ring current. The observed encounters by satellites with the bow shock, magnetopause, and plasmapause were reproduced in modeling studies. *Engel et al.* [2016] addressed the simulated and observed loss of protons in the inner radiation belt during the 2015 storm interval. Their study suggested the importance of the inductive electric field and also confirmed that the largest proton losses are indeed at the minimum *Dst* and the losses are pitch angle dependent. Examining the connection between solar events and extremely low frequency electromagnetic waves in the atmosphere, *Salinas et al.* [2016] found significant changes in the Schumann resonances in peak amplitudes and frequencies during both storm events in 2013 and 2015.
2. *High-latitude responses*. The energy inputs to the high-latitude regions created significant ionospheric disturbances during the two storms. *Lyons et al.* [2016] reported poleward and equatorward expansion of the auroral oval (enhanced nightside reconnection), auroral streamers, and highly structured field-aligned currents. Ground magnetometer measurements revealed current vortices during the sudden commencements of the March 2013 and 2015 storm [*Marsal et al*., 2016]. The Van Allen Probe observed pressure buildup and composition changes in the inner ring current during the 2013 event due to adiabatic convection [*Menz et al*., 2016]. *Zolotukhina et al*. [2017] reported intense sporadic layers and intervals of total radio absorption in Russia and Asia sectors. In addition to the typical enhanced GPS phase scintillations around the cusp and tongue of ionization (TOI) in the polar cap, *Prikryl et al.* [2016] found that GPS phase scintillations were also enhanced at the edge of auroral electrojets. *Heine et al*. [2017] identified ~1–10 km small-scale ionospheric irregularities along the poleward edge of the Storm Enhanced Density (SED) plume. In northern Germany, the 17 March 2015 storm also led to the occurrence of *E* region ionospheric irregularities (50–80 km size) of narrow spectral width with both low and high Doppler speeds corresponding to different parts of the *E* region [*Chau and St.-Maurice*, 2016]. *St.-Maurice and Chau* [2016] suggested that Farley-Buneman instability with nonthermal electrons and ions was the source of the irregularities.
3. *Subauroral and midlatitude processes*. Many subauroral processes having potential mesoscale or even global impacts are closely related to those at high latitudes and magnetosphere-ionosphere coupling. *Zhang et al.* [2017] found signs of atmospheric upwelling and ion upflow due to strong frictional heating during the Subauroral Polarization Stream (SAPS) event. Such upwelling could potentially contribute to the global disturbance pattern in thermospheric composition and wind circulation. A data assimilation/reanalysis approach was used to construct comprehensive ionospheric images in polar and other regions over both hemispheres. These showed clear conjugate occurrence of SED/TOI as well as signatures of plasma subcorotating from Europe to America [*Yue et al*., 2016a]. A Thermosphere-Ionosphere Electrodynamics General Circulation Model (TIEGCM) numerical simulation by *Liu et al.* [2016] highlighted the important role of upward drifts of the ionospheric plasma (such as those associated with the Prompt Penetration Electric Fields, PPEF). These plasmas also convect westward contributing to SED formation and evolution. A SAMI3-RCM self-consistent modeling study of the ionosphere-plasmasphere system indicates that the storm time penetration electric fields lead to a SED in the low- to middle-latitude ionosphere [*Huba et al*., 2016], in agreement with a separated study based on Millstone Hill radar observations [*Zhang et al*., 2017]. The model also reproduced TOI occurrence in the polar cap as well as the disappearance of the plasmaspheric plumes.
4. *PPEF and DDEF*. This Special Section achieved new insights into the storm time behavior of PPEF and disturbance dynamo electric field (DDEF) effects. Various observational studies deal with dynamical ionospheric changes at different geospace regimes, from subauroral to middle and low latitudes

[*Hairston et al*., 2016; *Huang et al*., 2016; *Kalita et al*., 2016; *Kuai et al*., 2016; *Zhou et al*., 2016; *Zhang et al*., 2017; etc]. *Hairston et al.* [2016] provided a comprehensive view of the DMSP and C/NOFS measurements of the global evolution of plasma drifts (electric fields) during the March 2015 storm. These showed PPEFs in the first few hours of the storm main phase. Using DMSP data, *Huang et al.* [2016] found that the DDEF occurred a few hours after the beginning of the storm main phase and lasted for almost 31 h, well into the storm recovery phase. *Kuai et al.* [2016] used ground-based ionospheric observations at low latitudes in Asia/Australia and America longitudes to indicate the effects of PPEF and long-duration DDEF in different longitude (day/night) sectors.

5. *Effects of neutral dynamics and perturbation*. Important additional processes driven by high-latitude energy and momentum inputs from the solar wind and magnetosphere are related to changes in global neutral wind circulation, temperature, and composition. *Zhong et al.* [2016] suggested that the topside ionospheric total electron content (TEC) reduction over a few days during the recovery phase of the storm is related to the corresponding O/N2 reduction effects in the bottomside ionosphere that map along field lines into the topside. The long-duration electron density reduction was also seen in N_mF_2 and TEC obtained globally from a data assimilation/ reanalysis approach by *Yue et al.* [2016b]. Their TIEGCM simulation suggests effects of storm time neutral winds and composition. This study and *Yao et al.* [2016] also indicated a hemispheric asymmetry of the electron density depression during the long recovery phase. A global self-consistent model of the thermosphere, ionosphere, and protonosphere has been used by *Dmitriev et al.* [2017] to demonstrate the low- and middle-latitude ionospheric disturbances caused by both storms in 2013 and 2015. The model captured qualitatively the ionospheric negative storm effect at middle latitudes. Physical model-based data assimilation was also performed to obtain storm time equivalent variations in the electric field and winds and to forecast ionospheric characteristics [*Chen et al*., 2016]. Storm time ionosphere and thermosphere perturbations also can be seen in the form of propagating waves. *Zakharenkova et al.* [2016] present a dedicated Large-Scale Traveling Ionospheric Disturbance (LSTID) study using Global Navigation Satellite System (GNSS) TEC to show intense and essentially global-scale LSTIDs and the convergence of LSTIDs in the interference zone over the geomagnetic equator in South America. *Yao et al.* [2016] similarly identified three periods of highly correlated *AE* index enhancement and TID activity, predominantly during the two main phases of the 2015 storm.
6. *Plasma bubbles and irregularities*. Low-latitude plasma irregularities were reported in a number of studies where the interplay and influences of PPEF, DDEF on the equatorial bubbles were discussed. *Kil et al.* [2016] indicated that storm time changes in electric fields which caused the uplifting of the ionosphere can yield two types of broad plasma depletions (plasma bubbles and nonbubbles) in the equatorial *F* region before midnight during the storm main phase. *Patra et al.* [2016] ascribed the plasma bubbles and irregularities to the rapid uplift of the ionosphere, which caused strong postsunset scintillations in a very narrow longitudinal zone in India. *Ray et al.* [2017] showed during the March 2015 storm a significant TEC enhancement during the day and intense phase scintillation at night. *Spogli et al.* [2016] indicated that PPEF could suppress in a statistical sense the occurrence of equatorial plasma bubbles and scintillation during geomagnetically disturbed days. This scenario of both initializing and suppressing plasma density instability at different stages of storms and local time sectors by either PPEF or DDEF is discussed thoroughly in *Zhou et al.* [2016].

3. Some New Achievements

We point out a few topic areas where some exciting new findings were made. Clarifying the different roles played by PPEF and DDEF at different stages of the storms on middle- and low-latitude ionospheric dynamics is a dominant theme in this special section. Observations and simulations included in this collection highlight the occurrence of PPEF and show that its effects are responsible for the development of SED features originated at middle and subauroral latitudes. In low and equatorial regions, plasma instability and other ionospheric variations were explained in terms of the PPEF effect that can be highly variable with local time and region. Furthermore, DDEF was found to occur at the very early stage of the storm and to be of long duration providing a significant influence, in competition with PPEF effects, on the low-latitude dynamics. Papers in this collection showcase the considerable complexity and variability of the system. This complexity and variability constitute a challenge requiring further understanding supported by comprehensive studies using both observations and modeling.

Middle and subauroral latitude irregularities were observed during storms in different forms but show a common link to strong disturbance electric fields (SAPS). These new independent observations of plasma instability associated with SAPS form a chain of compelling evidence in a way fully consistent with the irregularities viewed a decade ago as coherent echoes by the Millstone Hill radar [*Foster and Erickson*, 2000] and Super Dual Auroral Radar Network (SuperDARN) radars [*Oksavik et al*., 2006].

Another interesting finding is the long-lasting ionospheric negative storm effect observed on both the ionospheric F_2 peak density and, surprisingly, in the topside ionosphere TEC during the storm recovery phase. This negative storm effect is caused by storm time thermospheric composition influences on the bottomside ionosphere. The longitudinal dependence of the storm time effects and storm recovery is also very interesting and intriguing and in need of a good physical explanation. The hemispheric asymmetry and conjugacy in the storm effects are reported in a number of papers in this collection. Understanding the physical processes that leads to such effects is a challenging task, considering that both storms occurred almost exactly at the March Equinox.

4. Challenges and Future Work

To advance our understanding of the storm time geospace system, a number of future challenges have to be addressed properly. Gaining a system view spanning disciplinary boundaries needs further development along side to complement a diversity of in situ and ground-based observations. The studies presented in this special section demonstrate the powerful efficiency of using cross-scale measurements from multiple satellite platforms to develop a system perspective for the dynamic magnetosphere, plasmasphere, ionosphere, and thermosphere interactions that take place during such events. Such comprehensive observations are not only a contemporary capability but also a necessity in addressing this complex interconnected system. Simultaneous ionosphere and thermosphere measurements emphasize the physical processes at the important low-altitude interfaces of the system. Joint analysis of the interplanetary parameters and I/T parameters provides insights into the direct causative connection between them.

A further major challenge is the sparsity of data coverage in space/time and available parameters. Some of the studies in the collection offer feasible solutions to providing a better description of the much-enhanced storm time global structures of the thermosphere and ionosphere, e.g., data reanalysis/assimilation for reconstructing important global features (such as SED/TOI and other large-scale features which are typically difficult to measure) and extensive usage of the GNSS data to yield a spatially detailed and nearly a global picture of LSTID evolution. These examples of new capabilities will facilitate better understanding of the dynamics and variability of the global M-I-T system and guide modeling efforts of the underlying physical processes.

Throughout this collection, direct observation of the thermospheric parameters is quite limited. These studies rely on the widely used TIMED (Thermosphere Ionosphere Mesosphere Energetics Dynamics) GUVI (Global Ultraviolet Imager) data and Incoherent Scatter Radar (ISR)/Fabry Perot Interferometer (FPI) winds. This lack of observations of key drivers (electric fields, winds, and composition, for instance) causes quite some uncertainty in scientific interpretation. Sophisticated numerical models have been applied in the storm study and showed successfully some large-scale electron density features such as the long-lasting negative phase variations of electron density; however, further verification of those key drivers with direct observations is needed. With the launches of new satellite missions such as the Ionospheric Connection Explorer (ICON) and the Global-scale Observations of the Limb and Disk (GOLD), devolvement of arrays of small instruments such as FPIs, GNSS receivers, and digisondes, as well as sustained observations with major geospace facilities such as ISRs and SuperDARN (Super Dual Auroral Radar Network), the growing observational network will be delivering new exciting results in the coming years.

5. Concluding Remarks

In summary, we believe that this collection of papers reflects our latest and perhaps most sophisticated capability in the geospace storm monitoring and represents our state-of-the-art understanding of important storm time processes within the coupled geospace system. These achievements are an important stepping-stone that will lead eventually to improved prediction and forecast of the space weather effect. We are deeply appreciative of the authors for their contributions and of the reviewers for their time and effort in maintaining high quality of these publications.

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