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Editorial: Solar wind–Magnetosphere interactions

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Editorial on the Research Topic
Solar wind–Magnetosphere interactions

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The Earth's magnetic field shields the planet and its atmosphere from the solar wind. However, this magnetic shielding is not perfect. A fraction of the mass, energy, and momentum from the solar wind can transfer to the magnetosphere and ionosphere through processes that are often referred to as solar wind-magnetosphere interactions (see, for example, reviews in Akasofu, (1981); Rostoker et al. (1988); Gonzalez et al. (1999); Jordanova, (2003); Watermann et al. (2009); Wing et al. (2014); Johnson et al. (2014); Kilpua et al. (2017); Borovsky (2020); Zhang et al. (2022)). The solar-wind-magnetosphere interactions form a basic foundation for the studies of space physics, magnetospheric physics, ionospheric physics, and space weather.

The goals of this Frontiers Research Topic on Solar Wind–Magnetosphere Interactions are 1) to publish research at the forefront of this important topic, 2) to assess the state of knowledge, 3) to point out new directions in research, 4) to apply new mathematical and data-analysis techniques, and 5) to discuss needs for the future.

Seventeen papers on solar wind–magnetosphere interactions are contained in this electronic book. Synopses of the seventeen papers are as follows, ordered by papers that focus on 1) the Sun 2) solar wind, 3) magnetosphere, and 4) ionosphere.

Chapman builds on her previous work that shows that they can map sunspot record, which has irregular cycle duration, onto a regular "clock" where each cycle has the same duration in Hilbert analytic phase. The quiet interval of the solar cycle is located at a fixed phase interval of this solar cycle clock. In the present work, she shows that such mapping can be done without using the Hilbert transform. There is a clear geomagnetically active-quiet switch-off and quiet-active switch-on activity and the times for this on and off switch can be directly determined from the sunspot time-series without performing Hilbert transform. The switch-off and switch-on of activity can be mapped from the clock back into the time-domain to create a cycle-by-cycle chart of activity, which can be useful for space weather assessment.

Sivadas and Sibeck study how simultaneous measurements of different L1 solar wind monitors differ due spatial and temporal structure of solar wind. They point out that this inherent uncertainty in L1 solar wind measurements may lead to bias in various studies utilizing correlations between solar wind and magnetospheric variables. By numerical experiments Sivadas and Sibeck show that this so-called regression bias may lead to an apparent underestimation of magnetospheric response to extremes in solar wind driving for all popularly used regression analysis methods.

Chepuri et al. examine a large number of low-latitude boundary layer crossings by the Magnetospheric Multiscale (MMS) satellites to analyze the fluxes of energetic (>30 keV) electrons and whistler-mode chorus waves. They find that enhancements of energetic electrons and whistler-mode waves are often associated with signatures of magnetic reconnection. However, they point out that more research is needed to uncover whether these statistical relationships indicate causality.

Farrugia et al. study the effect of a solar wind directional discontinuity (DD) on the Earth's magnetosphere on 10 January 2004 using simultaneous observations from four spacecraft, namely Geotail, Cluster, Polar, and DMSP. The passage of the solar wind DD leads to the formation of the complicated structures in the magnetosphere even though the geomagnetic activity is relatively quiet, AE index is ~ 0 nT and Sym-H ~−10 nT. These structures include compression and dilation of the magnetosphere, deformation of the postnoon magnetopause, magnetotail flapping and twisting, strong tailward flow (~680 km/s) at a distant tail (~−230 Re). At the nightside ionosphere, near the poleward edge of the auroral oval, there is evidence of strong sunward flow (3 km/s) accompanied by a pair of upward and downward field-aligned currents (FACs).

Reistad et al. show that magnetospheric substorms are stronger and more frequent when IMF By and the Earth's magnetic dipole tilt have opposite signs. That is, substorm activity is enhanced for By > 0 during negative dipole tilt (NH winter) and *vice versa* during positive dipole tilt (NH summer). Reistad et al. show that this so-called explicit IMF By dependence is systematically seen in several, independent substorm lists. The physical mechanism of the By dependence is currently not fully understood. Reistad et al. suggest that the By dependence of magnetospheric substorms could result from a similar By dependence of the dayside reconnection rate.

Pulkkinen et al. perform 131 simulations of geomagnetic storms using the University of Michigan Space Weather Modeling Framework Geospace configuration. The framework comprises a set of numerical models able to solve the 3-D extended MHD equations to describe and predict different processes in space plasma. The study focuses on modeling the parameters characterizing the condition of the magnetosphere like the geomagnetic indices, which are directly related to solar wind drivers, magnetopause locations, and the cross-polar cap potential. The simulated results are generally in a good agreement with those observed. Meanwhile, it is found that the Geospace simulation consistently underestimates AL index, and significantly gives smaller distances from the Sun-Earth line to the lobe boundary in comparison with the empirical model in the conditions of the increased dynamic solar wind pressure. The article highlights the usability of geomagnetic indices and constructiing solar wind drivers of geomagnetic storms.

Borovsky re-examines the well-known positive correlation between the amplitude of magnetic-field fluctuations (turbulence) in the upstream solar wind and the level of geomagnetic activity. He re-confirms those correlations, but cautions the research community that the "turbulence effect" on magnetospheric activity may not be physically real.

Borovsky re-investigates the effect of noise on solar-wind/magnetosphere coupling studies by adding noise to real solar-wind and geomagnetic-activity data. This study re-confirms that noise changes the functional forms of best-fit driver functions, again obscuring the physics of how the magnetosphere is driven by the solar wind.

Borovsky uses artificial-data "gedankenexperiments" to explore the effect of noise in the data on correlation analysis between the time-dependent solar wind and the time-dependent geomagnetic activity. Noise is found to alter best-fit formulas for solar-wind driver functions, obscuring the physics of solar-wind driving.

Borovsky points out that there are 3 dawn-dusk aberrations to the solar wind at the Earth: one caused by the orbit of the Earth about the Sun, one caused by the propatation of solar-wind structure along the Parker spiral direction, and one associated with a systematic non-radial flow of the solar wind at 1 AU. These 3 aberrations degrade the quality of a solar-wind monitor at L1.

Gokani et al. discuss how solar drivers and geomagnetic storms affect the loss of high energy electrons from the outer radiation belt. They analyze 103 intense geomagnetic storms with Dst ≤ −100 nT in 1996–2019 and, using the superposed epoch analysis, find that the flux depletions of electrons having energies >0.6 MeV and >0.8 MeV at the geostationary orbit starts with the main phase of the storm and can reach over one order of magnitude. No solar cycle dependence is found. Effects of the most geoeffective solar drivers, namely coronal mass ejections (CMEs) and corotating interaction regions (CIRs), are investigated. Interplanetary coronal mass ejections (ICMEs) are divided into sub-structures and tested for the impact of each on the radiation belt electron flux. The authors conclude that the flux decreases are larger in the sheath-related storms, which may be due to the enhanced dynamic pressure and ULF wave power. A comparison between the radiation belt electron depletion caused by ICMEs and CIRs shows that it is more pronounced in the latter case, contrary to previous observations. The role of different solar drivers, such as solar wind conditions, the pressure, the speed, the density, the electric field, and the interplanetary magnetic field vertical component in causing radiation belt energetic electron flux decrease is also discussed.

Borovsky and Runov investigate the possibility that the energetic strahl electron population of the solar wind might be the ultimate origin of the seed electron population of the Earth's electron radiation belt, with the strahl electrons becoming the suprtathermal electron population of the magnetotail plasma sheet, electrons which are injected into the Earth's dipole by substorms.

Kondrashov et al. describe a machine learning technique to predict plasmaspheric hiss spectral classes ("no hiss", "regular hiss", and "low-frequency hiss") from the Van Allen Probes data. The authors create a random forests model which is found to be more accurate, compared to the existing unsupervised machine learning self-organizing map method. The highest scores detected by the model often match the distribution of the classes in the data set, which explains the model's high predictive skill. It is shown that predictors like magnetospheric and solar wind conditions only improve the predictions by a very small amount while the distinct locations of a given spectral class play a major role in determining the prediction's accuracy.

Lockwood and Cowley carry out a comprehensive analysis of non-equilibrium conditions of the magnetosphere-ionosphere-thermosphere system. The most important phenomena, such as magnetic reconnection and flux transport, occur when the system is not in equilibrium, therefore the corresponding processes require better understanding. It is shown that even if the solar wind driving does not change, the magnetosphere-ionosphere system can still display variations depending on time of year and UT owing to the Earth dipole tilt combined with other effects such as motions of the geomagnetic poles in a geocentric frame, the tail geometry, and ionospheric conductivity. This means that equilibrium is not just a function of the amount of open flux in the system. The study suggests that if one tries to map electric fields from interplanetary space to the ionosphere, the results are only accurate under steady-state conditions that can be achieved by taking data over long timescales and averaging out fluctuations. It is also discussed how the Expanding Contracting Polar Cap (ECPC) model may be the most accurate in predicting the magnetospheric response to the solar wind variability. In particular, it is found that the convection response and the integrated flux transport over the polar cap are higher for the high solar wind dynamic pressure cases. According to ECPC, enhanced solar wind dynamic pressure leads to a faster response time of the magnetosphere-ionosphere system since it controls the pressure in the magnetosheath that, in turn, determines how quickly the system returns towards equilibrium.

Partamies et al. study 68 events of high-latitude pulsating aurora (PsA) events using the optical observatory at Svalbard at 75° magnetic latitude (MLAT). They find that the high-latitude PsA events, which tend to occur between 5 and 11 magnetic local time (MLT), are associated with lower geomagnetic activity, weaker solar wind driving, lower ionospheric electron density than those with the low-latitude PsA events (located in the equatorward portion of the auroral oval). They conclude that the high-latitude PsA is dominated by a sub-type called Amorphous Pulsating Aurora (APA) and not likely to cause direct changes in the chemical composition of the mesosphere.

Dredger et al. present a study in which they investigate the connection of the field-aligned currents in the polar cap and the currents generated at the bow shock using MMS, AMPERE, and DMSP observations during a period of strong IMF By on 13 November 2015. The FAC flows downward and upward in the northern and southern polar cap, respectively while the bow shock current also has the same south-to-north polarity. They compare the magnitudes and polarities of the bow shock and field-aligned currents in the observations with those from the MHD simulation of the same event. They conclude that taken together, the observations and simulation support the hypothesis that the bow shock current, at least partially, closes through the ionosphere.

Bland et al. determine the spatial extent of energetic (>30 keV) electron precipitation during three substorms using cosmic noise absorption (CNA), the Super Dual Auroral Radar Network (SuperDARN) and very low frequency (VLF) measurements. They show that energetic electron precipitation extends significantly further equatorward than predicted by current empirical models, even during moderate geomagnetic activity. These results show that more research is needed to understand spatial distribution of energetic electron precipitation and its atmospheric response.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication. All authors performed the research and wrote the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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