Space Weather Energy Pathways and Implications for Impacts

Friday 08 January 2021

Talks

Emilia Kilpua (Invited), University of Helsinki

Large-scale solar wind structures as drivers of space weather storms

> The large-scale heliospheric structures that are most likely to driven intense space weather storms are Interplanetary coronal mass ejections (ICMEs) and their sheath regions. These structures have distinctly different origin and solar wind conditions, and consequently, they cause different responses in the near-Earth space environment. In this talk I will discuss key differences in space weather relevant parameters in these structures, how they control the solar wind – magnetosphere coupling processes and specific challenges in predicting their geoeffectivity. I will in particular highlight differences in geospace response (ring current, auroral region, radiation belts). In addition, I will discuss briefly the reasons why our capability to provide long-lead time space weather predictions (at least half-a-day in advance) is currently rather modest and how data-driven modelling of solar flux ropes in the low corona could help in this effort.

John Coxon, University of Southampton

The heavy-tailed distributions of Birkeland currents observed by AMPERE

> Field-aligned currents link the ionosphere to the magnetopause (Region 1) and the ring current (Region 2), and are a key part of the way in which energy is transferred into the ionosphere. We use data from the Active Magnetosphere and Planetary Electrodynamic Response Experiment (AMPERE) to quantify the way in which the field-aligned current densities are distributed in each spatial coordinate, and analyse the implications that this has for the parts of the system likely to see the largest amounts of current. We fit a Tsallis, or q-exponential, distribution to the current densities in spatial coordinate, to generate maps of the probability of field-aligned current densities above certain thresholds in both hemispheres. We discuss this in terms of its ramifications for space weather energy pathways.

Juliane Huebert, British Geological Survey

Investigating the Space Weather impacts on ground-based technologies in the UK - Measuring and modelling geomagnetically induced currents in power networks and pipelines

The technological impacts of space weather at ground level are the result of space physics processes driven by solar activity and by geophysical processes both external and internal to the solid Earth. Space weather causes Geomagnetically Induced Currents (GICs) that can damage power transformers and safety systems. It enhances voltage differences in metal gas transmission pipelines, which increases corrosion rates in pipe steel. Large surface electric fields during space weather may also trip rail circuits. To tackle questions such as where, how big and for how long do impacts last, requires a multi-disciplinary approach. The NERC ‘Space Weather Impacts on Ground-based Systems’ (SWIGS) project therefore brought together a broad spectrum of scientific expertise to answer such questions. We present the results of new approaches developed in the last three years to measure and model surface electric fields during geomagnetic storm times, GICs flowing in the GB power network and the Pipe-to-Soil Potential (PSP) across the gas transmission pipeline network.

Sarah Bentley, Northumbria University

Magnetospheric moderation of solar wind drivers in a statistical model of ULF waves

We present and analyse a freely-available model of the power found in ultra-low frequency waves (ULF, 1-15 mHz) throughout Earth’s magnetosphere. Predictions can be used to test our understanding of magnetospheric dynamics, while accurate models of these waves are required to characterise the energisation and transport of radiation belt electrons in space weather.

Our model is constructed using decision tree ensembles, which iteratively partition the given parameter space into variable size bins. Wave power is determined by physical driving parameters (solar wind speed vsw, magnetic field component Bz and variance in proton number density var(Np)) and spatial parameters of interest (magnetic local time MLT, magnetic latitude and frequency).

There is no guarantee that physical processes can be extracted from parameterised models such as this. However, by iteratively considering smaller scale driving processes, we find that solar wind driving of ULF waves are moderated by internal magnetospheric conditions. We conclude that the dawn-dusk asymmetry is probably due to the different radial density profile of the plasma combined with driving from magnetopause perturbations. Significant remaining uncertainty occurred with mild solar wind driving, suggesting that the internal state of the magnetosphere should be included in future.

Andrew Dimmock (Invited), Swedish Institute of Space Physics Uppsala

The geomagnetic response in Fennoscandia to the September 2017 storm: observations and modelling

Geomagnetically Induced Currents (GICs) are a space weather hazard that can negatively impact large ground-based infrastructures such as power lines, pipelines, and railways. They arise due to a geoelectric field, which is set up by geomagnetic induction between rapid geomagnetic variations on the surface and the ground conductivity. In this work, we analysed the ground impact over Fennoscandia during the geomagnetic storm of 7-8 September 2017. During this period, we observed 30A peak GIC in the Finnish natural gas pipeline at the Mäntsälä compressor station, and prolonged GIC intervals exceeding 10A. Based on IMAGE ground magnetometer measurements, the geomagnetic response revealed many spatially and temporally localised features, which we show are important to modelling GICs. We also modelled this event using the Space Weather Modelling Framework (SWMF). Using Biot-Savart integrals we were able to place virtual magnetometers at various locations and compare with observations. These simulations were run at low, medium, and high spatial resolution to determine the role in capturing spatially structured geomagnetic disturbances. This revealed that although higher resolution can improve predictions in some situations, substorms were not captured at higher latitudes (>65o) which dominates the observed response.

Frances Staples, MSSL, UCL

Key Signatures of Magnetopause Shadowing during the September 2017 Geomagnetic Storm.

Whilst acceleration mechanisms transfer energy into radiation belt electrons, those electrons are often rapidly removed by loss processes; either by precipitation into the Earth’s atmosphere or through the magnetopause, termed ‘magnetopause shadowing’. Magnetopause shadowing can also remove lower energy seed electrons, which limits energy transfer into the belt via acceleration processes. Whilst shadowing is well understood to produce dropouts in electron flux, it is less clear if shadowing continues to remove particles in tandem with electron acceleration processes, limiting the overall flux increase.

We investigate the contribution of shadowing to overall radiation belt fluxes throughout a geomagnetic storm. We use new, multi-spacecraft phase space density calculations to decipher electron dynamics during each storm phase and identify features of magnetopause shadowing during both the net-loss and the net-acceleration storm phases. We also highlight two distinct types of shadowing; ‘Indirect’, where electrons are lost through outward transport to the magnetopause boundary, and ‘direct’, where electrons are lost as their orbit intersects the magnetopause boundary. We highlight the complexity of energy pathways in the inner magnetosphere and demonstrate the importance of solar wind structures as not only an input of energy but also a crucial loss process for the radiation belts.

Allison Jaynes, University of Iowa

High-energy electron dynamics of the September 2017 geomagnetic storm

The geomagnetic storm that impacted Earth’s magnetosphere on September 8th, 2017 resulted in the acceleration of radiation belt electrons to very high energies, becoming one of the most energetic events in the seven years of the Van Allen Probes mission. Electrons of energies up to ~8 MeV were observed by the REPT instrument starting on 8 Sept, within hours of minimum Dst. Examination of the phase space density data during this time period indicates the drivers of this sudden acceleration, as well as the subsequent “filling” of the entire outer belt across a wide range of energies over the following days. One of the most interesting features of this storm occurs in the aftermath: the storm results in a highly energetic remnant belt that remains at low Lshells at detectable levels for over eight months of time. This is by far the longest-lasting remnant belt of the mission, and can be used to analytically examine the diffusion rates of these high-energy electrons within the plasmasphere.

Poster Presentations

Mayur R. Bakrania, Mullard Space Science Laboratory, UCL

Applying unsupervised learning and outlier detection methods to characterise magnetotail plasma sheet electrons

Collisionless space plasma environments are characterised by distinct particle populations that typically do not mix. Although moments of their velocity distributions help in distinguishing different plasma regimes, the distribution functions themselves provide more comprehensive information about the plasma state. Unlike moments, however, distributions are not easily characterised by a small number of parameters, making their classification more difficult. To perform this classification, we distinguish between the different plasma regions by applying dimensionality reduction and clustering methods to electron distributions in pitch angle and energy space. We test our algorithms by applying them to data from the Earth's magnetotail. Traditionally, it is thought that the magnetotail is split into three regions that are defined by their plasma characteristics. However, we identify 8 distinct groups of distributions, that are dependent upon more complex plasma and field dynamics. We find clear distinctions between our classified regions and the ECLAT results. The automated classification of different regions in space plasma environments provides a useful tool to identify the physical processes governing particle populations in near-Earth space. Using outlier detection methods, we identify anomalous distributions that are consistent with simulations of the tearing instability. We explore the energy and temperature profiles during these times.

Xiangcheng Dong, RAL Space

Field-aligned current ordering and intense ground dB/dt variations

Individual events sampled by higher altitude spacecraft (e.g. the 4 Cluster spacecraft), in conjunction with Swarm (mapping both to region 1 and 2), show two different domains of FACs: time variable, small-scale (10s km), and more stationary large-scale (>100 km) FACs. Both the statistical trends, and individual conjugate events, show comparable effects seen in the ground magnetometer signals (dH/dt) during storm/substorm activity and show distributions that are similar. Demonstration of intense dB/dt variations which are directly driven by bursty bulk flows (BBFs) at geosynchronous orbit is rare. The characteristics and response during the recovery phase of a geomagnetic storm that occurred on 7 January 2015 were covered by multi-point measurements, combining Cluster and SWARM measurements, and a group of ground-based magnetometer observations. The locations of Cluster and SWARM map to the same conjugate region as the magnetometer ground stations at the time of the BBF. The measurements show that corresponding signals in all measurements occur simultaneously (with suitable time lags) in this region. The most intense dB/dt (dH/dt) variations are associated with FACs corresponding to a modified SCW that are driven by BBFs at geosynchronous orbit around substorm onset.

Tom Elsden, University of Leicester

Modelling the Varying Location of Field Line Resonances During Geomagnetic Storms

Ultra-low frequency (ULF) waves play a major role in transporting energy and momentum throughout the Earth’s magnetosphere, through interaction with energetic particles in the radiation belts, the generation of strong, localised field-aligned currents and Joule heating of the ionosphere.

Recently, the enhanced mass density, evolving topology and corresponding suppression of the Alfven continuum through the enhancement of the ring current was invoked to explain the strong penetration of ULF wave power into low-L. However, the energy pathways are significantly more nuanced.

We construct novel MHD simulations of ULF wave processes that are constrained by observational statistics to consider how ULF wave energy pathways are affected by geomagnetic storms. Using a broadband source, we uncover a complex, interdependent system based on two principal wave resonances; fast waveguide modes with which the magnetosphere naturally responds to the broadband driving, and Alfvén resonances (FLRs) which such fast waves excite. We find that the waveguide frequencies and hence fast-Alfven wave coupling locations show a large dependence on storm phase, with FLR locations moving significantly Earthward for even modest storms. We discuss the implications of these results with respect to storm-time evolution of energy pathways into the magnetosphere through MHD wave processes.

Colin Forsyth, UCL

Quantitatively comparing the temporal and spatial variations of the aurora, waves and magnetic deflections associated with substorms

The auroral substorm can be thought of as an amalgamation of energy conversion processes in the magnetosphere-ionosphere system. At its simplest, stored magnetic energy is converted into particle and wave energy which impinge on the ionosphere and are converted into auroral emissions, ionospheric currents and Joule heating. The auroral, wave and current signatures all show an enhancement then subsequently wane after substorm onset and seem to show an initial spatial localisation before spreading to multiple local time sectors. However, while broadly similar, the specifics of these variations differ for each of these signatures. In this study, we show that the auroral intensity shows similar variations to ULF wave amplitude in the substorm onset sector, peaking in the minutes after onset, but more closely follows the ground perturbations associated with ionospheric currents towards dusk and dawn. The ground magnetic perturbations show a very different pattern to the auroral emission and wave amplitudes, peaking in amplitude some 20-30 min after onset and several hours of local-time east of the onset sector. These results show that multiple energy pathways, separated both in time and space, exist for substorms and thus the timings for different space weather impacts may vary.

James Waters, University of Southampton

Multipoint Remote Observations of Auroral Kilometric Radiation

Auroral Kilometric Radiation (AKR) is radio emission that originates in particle acceleration regions along magnetic field lines that coincide with discrete auroral arcs. Found in both hemispheres, an increase in the amplitude of a particular AKR source is indicative of the presence of strong, parallel electric fields in the auroral zone, while the emission frequency of AKR gives direct insight into the altitudinal extent of the source region. The viewing geometry is complex, however, due to the primary confinement of the source regions to nightside local times and the anisotropy of the beaming pattern seen at each pole, and it is not clear how the intensity of longitudinally-seperated source regions is related. During a month-long period in 1999, the Cassini spacecraft performed a close flyby of Earth and recorded AKR for the majority of the period, while the Wind spacecraft completed close to two, precessing petal orbits. An effective empirical proxy of the source variability is applied to Wind observations to select AKR emission and compare the integrated power with previously-studied measurements from Cassini. This provides an opportunity to further explore the viewing geometry of AKR as well as the temporal relationship between AKR ignition at different local times.

Clare Watt, Northumbria University

A comparison of magnetospheric ULF wave activity during storm and non-storm times

Ultra-low frequency (ULF) waves are ubiquitous throughout Earth’s magnetosphere and are one of the many methods by which solar wind energy can enter the Earth’s magnetospheric cavity. Importantly for space weather applications, ULF waves play an important role in the radial diffusion of radiation belt electrons. These waves, with frequencies of around 1-10mHz, can be easily detected using ground-based magnetometers that are in regions that magnetically map out to the outer radiation belt. Controlling factors for these waves have recently been found to include the instantaneous values of solar wind velocity, southward interplanetary magnetic field and variations in number density through a data-driven empirical study (Bentley et al., JGR 2018 and Bentley et al., SW, 2019). We specifically isolate geomagnetic storms and investigate whether the relationship between the solar wind factors and ULF waves is different during storms than it is during other times. In addition to demonstrating similarities and differences between storm times and non-storm times, we also show that the distribution of wave power changes during storms and discuss the implications for transport and energisation of electrons in Earth's Radiation belts.