RAS Specialist Discussion Meeting report

John C. Coxon, **Anasuya Aruliah**, **Sarah Bentley** and **Robert M. Shore** report on the RAS Specialist Discussion Meeting 'System-scale observations and modelling of solar wind-magnetosphere-ionosphere-thermosphere (SW-M-I-T) coupling'.

It was a glorious day at Burlington House: the sun was shining and the birds were singing. Unfortunately we were all on our computers and, in many cases, an entirely impractical walk from the nearest Pret a Manger.

Thus was set the scene for the April 2021 specialist discussion (G) meeting on 'System-scale observations and modelling of solar wind-magnetosphere-ionosphere-thermosphere (SW-M-I-T) coupling', which was held a year late owing to complications caused by the Covid-19 pandemic. Convened by the authors of this article, it aimed to bring together expertise from around the UK and globally on topics such as big data, machine learning, and datasets that provide hitherto unparalleled views of the coupled SW-M-I-T system.

This G meeting was the follow-up to an out-of-town meeting convened by Shore, Aruliah, Coxon and Elizabeth Tindale and held at the British Antarctic Survey in 2019. That meeting proved enormously popular, with the invited talk being given by Brian Anderson, the principal investigator of the Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) dataset: one of the key pieces of the system-scale data jigsaw. AMPERE is a dataset that provides global, interhemispheric views of the Birkeland current system. Birkeland currents, also known as field-aligned currents, electrodynamically communicate stresses from the magnetopause and magnetosphere into the ionosphere, and are vital to understanding how the solar wind affects Earth.

Our keynote was given by Colin Waters (University of Newcastle, Australia), who introduced AMPERE and gave an update on some of the recent developments in the dataset.

He talked about the genesis of the dataset, noting that he and Brian Anderson first discussed the idea in the late 1990s before work started on the project in 2000, when Waters spent a sabbatical working with Anderson at Johns Hopkins University Applied Physics Laboratory. AMPERE is derived using data from the Iridium satellite telecommunication network, and Waters took the time to introduce the different types of AMPERE data. The first data, from 1997 to 2008, was sampled at 200s and only derived from cross-track magnetic perturbation data, giving relatively coarse resolution (Anderson *et al.* 2000; 2002). From 2009 onwards, data sampling was available at 20s with the opportunity for burst mode, and the magnetic perturbation was measured in 3D (Green *et al.* 2006; Waters *et al.* 2001; 2020).

Since 2017, a new Iridium NEXT constellation enables sampling at 8s at all times, and Waters has expanded the pipeline which converts preprocessed AMPERE data in GEI coordinates into fitted AMPERE data in AACGM coordinates (Baker & Wing 1989; Shepherd 2014), changing the centre of the fitting process to better match the centre of the current systems and introducing an extra fitting step using Spherical Elementary Current Systems (SECS, Pulkkinen *et al.* 2003). These two steps are particularly relevant to the Southern Hemisphere fits, in which the centre of the system could have been as much as 15° different from the centre used for the fitting process.

Waters showed examples of the improved Southern Hemisphere data, noting that it recovered more current structure than the previous processing. Preliminary analysis suggests that the total amount of current increases by 5–10% in the Southern Hemisphere when averaged across all magnetic local time (MLT), but this does not eliminate previously observed hemispheric asymmetries in total current (Coxon *et al.* 2016), suggesting that those asymmetries are physical rather than as a result of artefacts from the data processing.

Waters was followed by Daniel Billett (Saskatoon), who described how a new dataset of Northern Hemisphere Poynting flux maps has been generated encompassing nearly eight years at a two-minute resolution (Billett *et al.* 2021).

This has been achieved using the current entirety of the overlapping Super Dual Auroral Radar Network (SuperDARN) and AMPERE datasets for measurements of the ionospheric electric field and perturbation magnetic fields. These have been examined statistically, noting that there is a consistent enhancement of the downward Poynting flux in the dayside cusp region for all interplanetary magnetic field (IMF) orientations. Comparisons have been made between the Poynting flux and the cusp neutral density enhancement as observed by the CHAMP satellite, and although it is clear that enhanced Poynting flux is related to the cusp density anomaly, they are not well correlated on medium to large scales. This gives insight to other processes that could account for the discrepancy and be an important driver of thermospheric dynamics, like small-scale field-aligned currents or soft-particle precipitation.

The first talk after the coffee break was given by Martin Archer (QMUL), who presented theory, simulations and observations of magnetopause surface eigenmodes.

These are surface waves with standing structure along the geomagnetic field due to bounding by the ionospheres (Chen & Hasegawa 1974; Archer *et al.* 2019), which do not conform to the well-accepted paradigm of tailward propagation of disturbances in global magnetospheric dynamics. They show that impulsively excited surface waves' Poynting vectors are in opposition to the magnetosheath flow, perfectly balancing its advective effect, thereby forming an azimuthally stationary surface wave (Archer *et al.* 2021). Simulations and theory agree that this stationary wave occurs across a wide MLT range (09–15), as shown in figure 1. Further down the flanks, however, advection dominates and the usual tailward travelling disturbances occur. Interestingly, these occur at the same frequency as the eigenmode originating on the dayside, demonstrating that it seeds fluctuations that may subsequently grow via the Kelvin-Helmholtz instability, despite being at a lower frequency to the peak growth rate. This reveals that surface eigenmodes' effects are not confined merely to the dayside (standing) region, instead having global effects on the magnetosphere as its most fundamental normal mode.

Next came Andrey Samsonov (MSSL/UCL), who explored the ramifications of magnetopause motion on geostationary satellites as part of the response of the coupled magnetosphere-ionosphere (M-I) system to strong solar wind variations such as interplanetary coronal mass ejections (ICMEs) and stream interaction regions (SIRs).

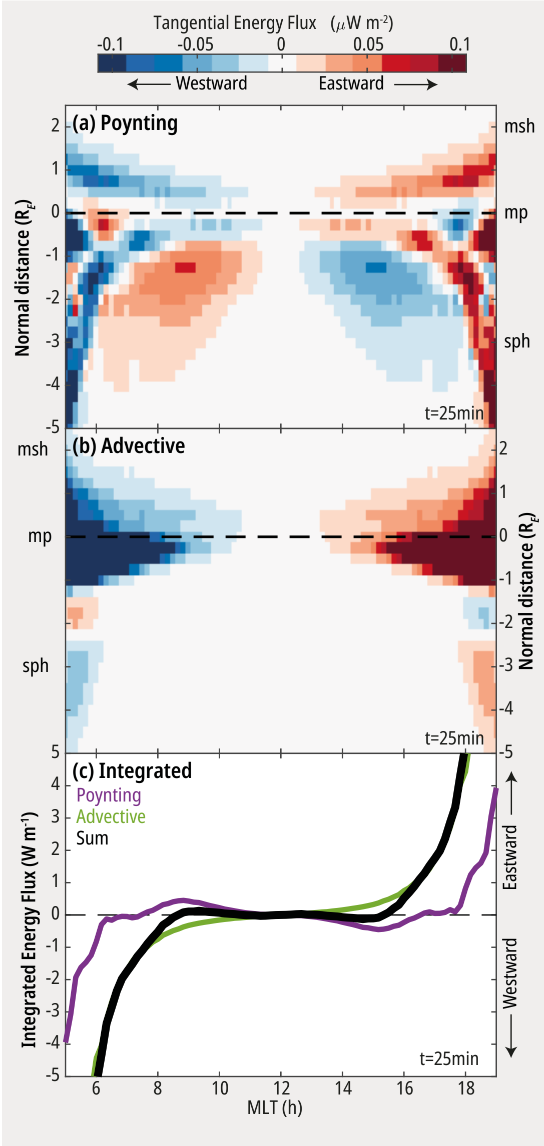
He presented connections between extreme magnetospheric compressions and global magnetospheric disturbances, substorms, and magnetic storms. Magnetopause shape and position strongly depend on the solar wind conditions and many empirical models have been developed to describe the magnetopause position. Samsonov used an existing model to predict the magnetopause standoff distance as a function of the solar wind dynamic pressure and magnetic field from 1995 to 2018 (Lin *et al.* 2010). Hourly averaged OMNI data were used to find time intervals when the predicted magnetopause standoff distance was less than 6.62 R_E. This is the distance of geosynchronous equatorial orbit (GEO) where many communication, navigation, and weather satellites are located. If the magnetopause crosses GEO, it is called a geosynchronous magnetopause crossing (GMC), and Samsonov examined 99 GMC events. He found that 74 events were associated with ICMEs, 18 events with SIRs, and 76 events with interplanetary shocks: all the GMCs were related to at least one of these solar wind sources. The GMC events were mostly followed by severe substorms and moderate or strong magnetic storms (within 24 hours). He analyzed the time lags between the GMC time and the following extremes of magnetospheric indices, showing that auroral activity rapidly increases after the extreme magnetospheric compression, while the maximum of ring current amplification occurs only several hours later.

New ways to approach data given that we are now in a 'data-rich' era was the subject of talk by Sandra Chapman (Warwick).

Networks can be used to characterize (many) multipoint, non-uniformly spatially distributed observations. To form the network they constructed a time-varying cross-correlation matrix, then thresholded it using the best suitable method: in this case, Haar wavelet cross-correlation. Ground-based magnetometer observations of large storms were used to drive a model for the geomagnetically-induced current (GIC) response in the UK National Grid (figure 2). They found intermittent, long-range connections: communities of supernodes where members tend to all be connected to each other. The spatial pattern did not simply follow the wavelet power (i.e. dB/dt), nor the physical connectivity of the grid. This approach can potentially characterize which parts of the grid respond coherently to a geomagnetic storm. This work provides an initial proof of concept and there is considerable scope for quantitative analysis across multiple events.

The meeting was introduced to the Solar wind Magnetosphere Ionosphere Link Explorer (SMILE) spacecraft by Graziella Branduardi-Raymont (MSSL/UCL).

Charge exchange soft X-ray emission has been found to be produced in the interaction of solar wind high-charge ions with neutrals in the Earth's exosphere; this has led to the realization that imaging this emission will provide us with a global and novel way to study solar-terrestrial interactions. In particular, X-ray imaging will enable us to establish the location of the magnetopause. Variations of the magnetopause standoff distance indicate global magnetospheric compressions and expansions, both in response to solar wind variations and internal magnetospheric processes.

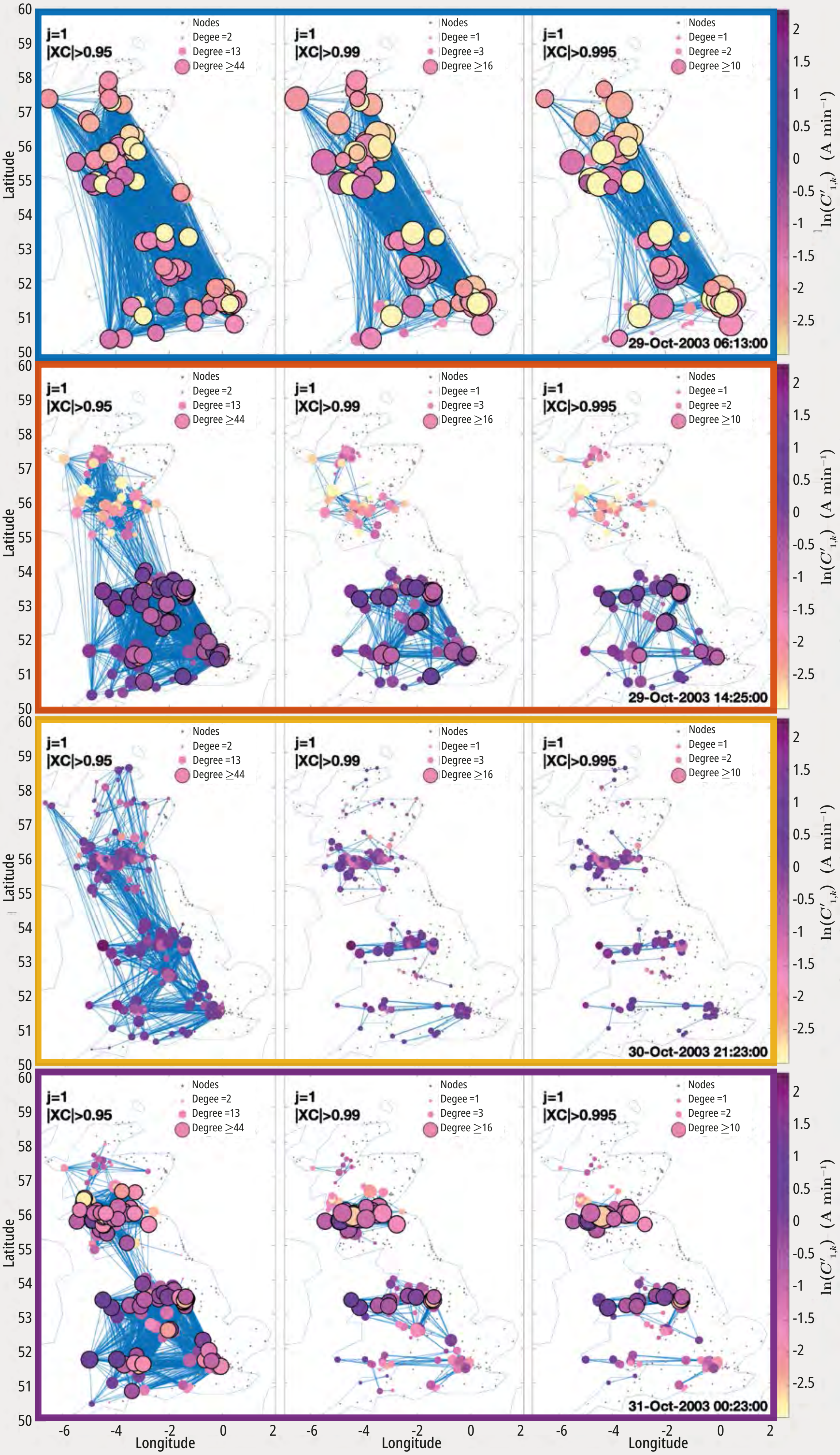


1 *Maps of* **(a)** *time-averaged wave Poynting and* **(b)** *advective energy fluxes tangential to the magnetopause and* **(c)** *their integrals along the normal in a global MHD simulation, from Archer et al. 2021.*

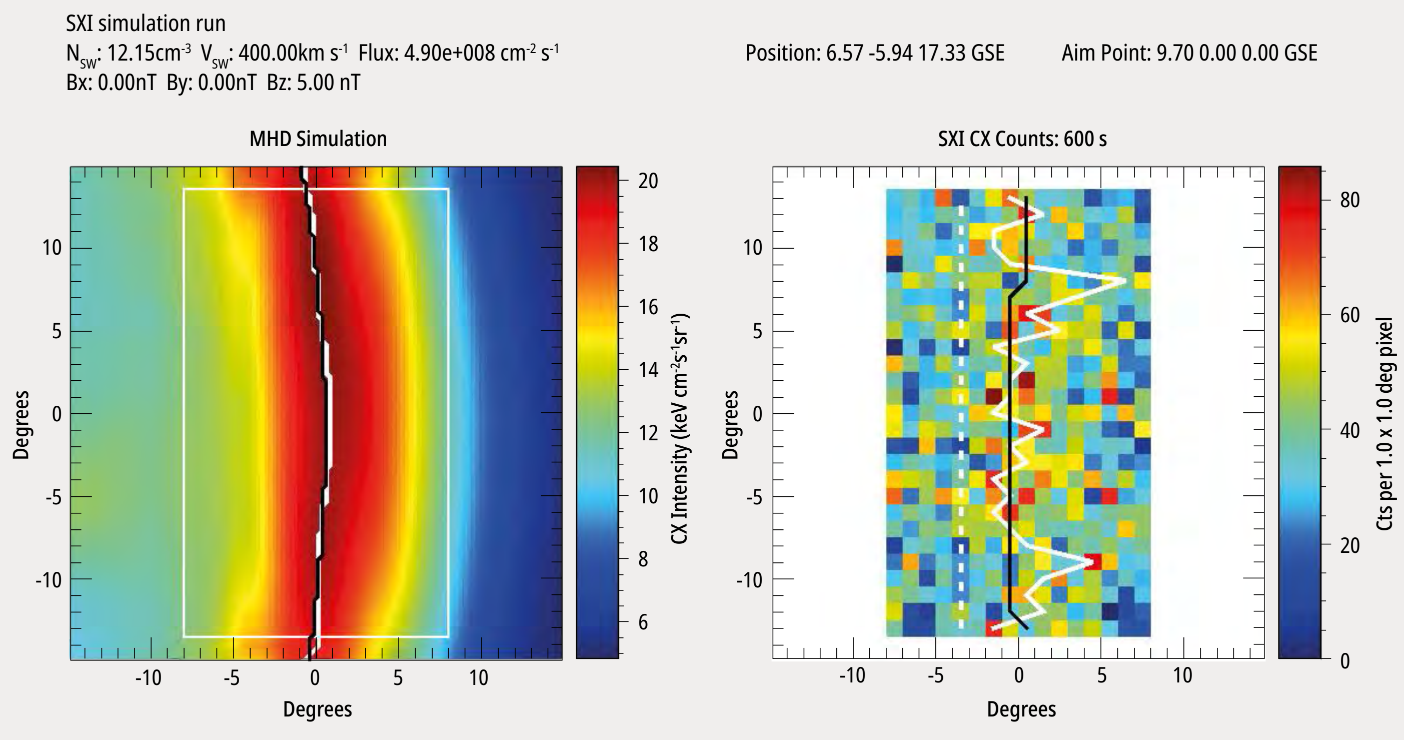
Such soft X-ray imaging is one of the main objectives of SMILE, a joint space mission by ESA and the Chinese Academy of Sciences, which is under development and is due for launch in 2024. From a highly elliptical polar orbit, simultaneously with the X-ray imaging, SMILE will provide continuous monitoring of the northern auroral oval in the UV, and *in situ* plasma and magnetic field measurements, in a new and global approach to studying the coupling of the solar wind with the terrestrial magnetosphere and ionosphere. Simulations of the soft X-ray images expected from SMILE were presented at the RAS Specialist Discussion Meeting. Figure 3 is an example of an ICME event that hit the Earth in 2012.

Steve Milan (Leicester) talked about the horse-collar auroral (HCA) configuration, in which the usually circular dim region enclosed within the auroral oval becomes teardrop-shaped.

It was discovered when cameras were first launched into space in the 1980s, and occurs during the quiet geomagnetic conditions that arise when the IMF is



2 *Snapshots of the network calculated from wavelet cross-correlation of the GICs at 398 grounded nodes measured across the UK from 29–31 October 2003. From top to bottom each row of plots corresponds to the times: 06:13, 14:25, 21:23 and 00:23 UT. These network configurations are rapidly changing and only persist for a few minutes. Grid nodes are plotted with the network connections between them for which the cross correlation exceeds 0.95 (left), 0.99 (centre) and 0.995 (right). Colour indicates the estimated rate of change of a wavelet. The size of the circles indicates the local degree (number of network connections) of each node. The legend plots the circle size for the 10th, 50th and 90th quantiles of the local degree distribution and black circles overplot nodes with degree exceeding the 90th quantile, where these quantiles are taken over the full duration of the storm.*



directed strongly northwards. It has been speculated for many years that HCA is caused by dual-lobe reconnection, when the IMF becomes simultaneously linked to both the northern and southern portions of the terrestrial magnetic field; if this is correct it could be a very efficient method of entraining dense solar wind plasma within the magnetosphere, significantly increasing its plasma density, which would be consistent with the observation of a 'low-latitude boundary layer' and 'cold, dense plasma sheet' observed within the magnetosphere during extended periods of northwards IMF. Milan provided a conceptual model of the expected ionospheric flow patterns and auroral evolution following a northwards turning of the IMF and demonstrated that these are consistent with observations from spacecraft of the Defense Meteorological Satellite Program (DMSP). These observations were supplemented by ionospheric flow measurements from SuperDARN and field-aligned current measurements from AMPERE, which are also consistent with the model predictions. Despite geomagnetic activity being low, these periods corresponded to a significant rearrangement of the structure of the magnetosphere. Milan's findings suggest that the evolution of horse-collar auroras should be linked to the location of trapped plasma within the magnetosphere, which in future will be tested with simultaneous *in situ* particle measurements. The occurrence of HCAs could herald periods when the magnetospheric plasma density is high, which can affect subsequent geomagnetic activity. Milan also speculated that if dual-lobe reconnection proceeds for long enough, the magnetosphere can become entirely closed, that is, no longer interlinked with the IMF.

Lauren Orr reported results from the Space Weather Instrumentation, Measurement, Modelling and Risk: Thermosphere (SWIMMR-T) programme, which aims to improve the UK's ability to forecast the thermosphere.

Thermospheric forecasts are made possible by the Advanced Ensemble electron density [Ne] Assimilation System (AENeAS), which is an assimilative model. It currently uses the Hairston & Heelis (1990) and Weimer (2005, hereafter W05) empirical electric field climatology models but it is possible more recent models, such as the Thomas & Shepherd (2018, hereafter TS18) model will improve functionality. Orr presented a quantitative comparison of the electric field models, exploring methods of standardizing the model input parameters to allow for fair comparison; in particular representing the transpolar voltage in terms of solar wind and IMF conditions. Orr detailed the differences and similarities in the convection maps produced by each model for a time interval during the 7 September 2017 storm. The time series of the transpolar voltage during the storm showed the TS18 model to have a much lower peak value than the W05 model, while estimates from relationships with solar wind and IMF conditions were often twice that of W05. Further work will include comparison with the TIme-variable Ionospheric Electric Field (TIVIE) model, an Empirical Orthogonal Function (EOF) model and the SuperDARN Map Potential model.

3 *X-ray emissivity map on the left, expected count map from the SMILE Soft X-ray Imager on the right; white lines, marking maximum emissivity profiles, and black lines, polynomial fits to them, give an indication of the location of the magnetopause*

Joe Borovsky looked at a system-science approach to studying solar wind-magnetosphere coupling, which they have been working on with Mick Denton.

Borovsky and Denton have developed a methodology to reduce a state-vector description of the time-dependent driven magnetospheric system (which accounts for multiple types of activity in the system) to a composite scalar picture description of the activity in the system. The technique uses canonical correlation analysis (vector-vector correlations) to reduce the multidimensional time-dependent solar-wind state vector and the multidimensional time-dependent magnetospheric-system state vector to time-dependent driver and system and scalars, with the scalar describing the global response of the magnetospheric system to the solar wind. This description that is a reduction from the state vectors has advantages: low noise, high prediction efficiency, linearity in the described system response to the driver, and compactness. The scalar description of the magnetosphere also has robustness with respect to: (a) storm-versus-quiet intervals; (b) solar maximum versus solar minimum; and (c) the various types of solar-wind plasma. They are in the process of developing a single system-wide index for community use to gauge magnetospheric activity.

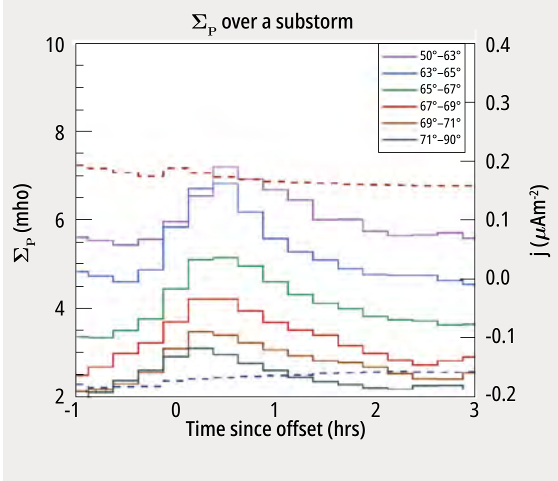
Finally, two posters were presented at the workshop. Téo Bloch (Reading) presented a poster that created a nowcasting Bayesian neural network model to predict the flux at the outer boundary location of the radiation belt (parameterized by either the solar wind or geomagnetic indices).

This was based on previous work (Bloch *et al.* 2021) suggesting that the current outer boundary condition used in many radiation belt models does not represent the true boundary location. As space-based infrastructure (and society's dependence on it) becomes more ubiquitous, it is ever-more important to be able accurately to model the environment within which spacecraft will pass their lifetime. For spacecraft in geosynchronous orbits or those which utilize electric orbit raising, specifically, understanding the outer (electron) radiation belt is critical. Bloch's poster demonstrated a model that provides a temporally-dynamic, synthetic spacecraft dataset of the 30–720 keV omnidirectional electron flux at 8.25 R_E which also resolves MLT. Additionally, the model was probabilistic, indicating the confidence in each prediction and providing a distribution of potential values. On average, Bloch's model predicted the fluxes within a factor of 2.5 for the lower energies and within a factor of 4 for the higher energies. The correlation between prediction and measured values was 0.5–0.8 across the energy channels.

Jenny Carter (Leicester) showed how auroral emission data, as observed by the Special Sensor Ultraviolet Spectrographic Imager (SSUSI, Paxton *et al.* 1992) onboard DMSP spacecraft, can be used to estimate height-integrated conductances in the high-latitude ionosphere.

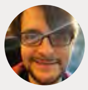
The spacecraft orbit at about 830 km altitudes. Although this offers a limited view of the ionosphere, after several high-latitude passes and by using the three available spacecraft, reasonable coverage of the polar caps can be obtained for the Northern Hemisphere dayside, and Southern Hemisphere nightside. Each SSUSI pixel is time-tagged, allowing climatological maps of the ionosphere to be parameterized by incoming IMF and solar wind conditions and season for the dayside (Carter *et al.* 2020), or substorm phase for the nightside. The substorm onsets were taken from the SuperMAG database (Gjerloev 2012) and maps of the conductance were built up using a superposed epoch analysis at a step size of 0.25 hr. Mean conductances were shown to peak approximately 0.5 hr after substorm onset, with maximum conductances seen in the 23 MLT sector (figure 4). If separate maps for substorms are constructed by also considering the magnetic latitude of onset, Carter showed that conductances at the lowest latitude onsets peak later than those at higher latitudes, and that the variation in conductances is driven by the mean energy flux of the particles precipitating into the ionosphere. This difference may be caused by convection braking (Milan *et al.* 2019). Equivalently binned AMPERE-derived Birkeland currents showed fairly flat profiles of Birkeland current magnitudes over the course of a substorm, although higher magnitude Birkeland currents are seen for lower-latitude onsets. Future work will consider the evolution of the conductances as a fraction of a substorm-defined time step, for example, related to the growth phase, following a suggestion by Martin Archer.

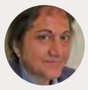
At the end of the meeting we chaired a discussion on how to continue discussing this science as a community and making progress collaboratively in this sense. There were various suggestions, including the formation of an International Space Science Institute (ISSI) working group. The Royal Astronomical Society has recently kindly made funding available to the Magnetosphere, Ionosphere and Solar-Terrestrial (MIST) and UK Solar Physics (UKSP) communities in order to fund three-year Zoom licences for both groups, and that was also identified as another potential route forward. The idea of collaborating as a larger community, sharing resources, results and perhaps code sharing and review, has huge potential and we are grateful to the RAS for providing a forum for starting this discussion. ●



4 *Height-integrated Pedersen conductance over the course of an average substorm, taken in the 21–02 MLT sector, split by magnetic latitude (coloured key). Birkeland currents for up (red) and down (blue) are shown in the dashed lines. Lower latitude substorm onsets (purple, blue) peak later than those at lower latitudes (grey, brown).*

AUTHORS


John Coxon is an Ernest Rutherford Fellow at Northumbria University. He is best known for his work on Birkeland currents and public engagement through the Southampton Planeterrella, and notorious for enjoying crosswords, board games and coffee.


Anasuya Aruliah is an Associate Professor in the UCL Department of Physics & Astronomy Astrophysics Group. She runs a long-term monitoring network of Fabry-Perot Interferometers in Arctic Scandinavia to observe the top layer of the Earth's atmosphere where the International Space Station and Earth Observations Satellites orbit. Viewing aurora is one of the great bonuses of this job.


Sarah Bentley is a Vice-Chancellor's Fellow at Northumbria University and investigates radiation belt physics and different methods of characterizing space weather. This requires a constant flow of tea, maths jokes and an unhealthy amount of cheese.


Rob Shore is a postdoc in the Space Weather and Atmosphere team at the British Antarctic Survey, currently working on the SWIMMR projects. He likes cycling in warm sunny places, and board games otherwise.

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