A & G article for SDM Global Monitoring of Geospace

Jenny Carter, Maria-Theresia Walach, Michaela Mooney, & the participants of the meeting

On 14th January 2022 we held a RAS Specialist Discussion Meeting entitled Global Monitoring of Geospace. We had hoped to be the first hybrid event the RAS had run since the start of the pandemic, but given the unsettled situation at the end of 2021, we reverted back to the original plan of a virtual-only meeting. We were very glad to see colleagues from across Europe and North America attend.

The aims of the meeting were to set the scene of current global system-level geospace science and later discuss what radical advances are being made in the field, or where significant efforts can be best directed to fill in the gaps of our understanding.

The morning opened with our first invited speaker, Aurélie Marchaudon (IRAP, CNRS, NESE, University of Toulouse, France), who gave a fantastic talk detailing the key regions of geospace that the community traditionally uses to divide up their attention. The domains of magnetic reconnection and substorm activity, auroral electrodynamics, the radiation belts, and the electrodynamics at the equator were identified. At magnetospheric scales, the community widely uses magnetohydrodynamic (MHD) models, and there is a move towards kinetic or hybrid models, but these are currently computational expensive and make large simplifications at boundaries. Global ionosphere-thermosphere models are currently simplistic and struggle to couple between domains consistently. They still need to incorporate lower atmosphere forcing from below, for example from tides or sudden stratospheric warmings, and more detailed forcing from above through high-latitude electrodynamics. A key issue in the field is data assimilation to improve the current models. Marchaudon stressed the need to incorporate as many different sources during data assimilation, from both ground-based and satellite-based measurements. These measurements, however, are often sparse, necessitating the development of new methodologies. The need for validation using different and independent data sets during this process was also emphasised. Marchaudon finished with an appeal for improved system-scale forecasts of spatio-temporal variations which could be achieved by applying Machine Learning to geomagnetically calm and disturbed conditions equally.

Malcolm Dunlop (STFC/RAL Space, UK) described a period of intense ground signals and field-aligned currents during a substorm, observed during a conjunction of multiple spacecraft at vastly different orbits (Cluster, Swarm), as well as by ground-based measurements (SuperMAG). At high-altitude, Cluster sees a substorm driven Bursty Bulk flow of plasma which drives electric currents in to the ionosphere at auroral latitudes. The currents were also detected by Swarm at low-Earth altitude. Simultaneous ground-induced currents were detected by the SuperMAG network of ground magnetometers in a spatially confined region as changes in the horizontal component of the Earth's magnetic field. These observations are consistent with field-aligned currents driven in the nightside substorm wedge, as shown in Fig. 1, implying a coherence of structures at vastly different altitudes. In addition, characteristic signatures of dipolarisation fronts associated with the substorm were also simultaneously detected by the RBSP-B and GOES-15 spacecraft. The advantages of the Swarm constellation in resolving detail in the structures of field-aligned currents was highlighted using the presented case over global measurements with lower spatial resolution.

Malcolm concluded by describing opportunities for future multi-spacecraft coordinated studies to explore the cusp and inner magnetosphere.

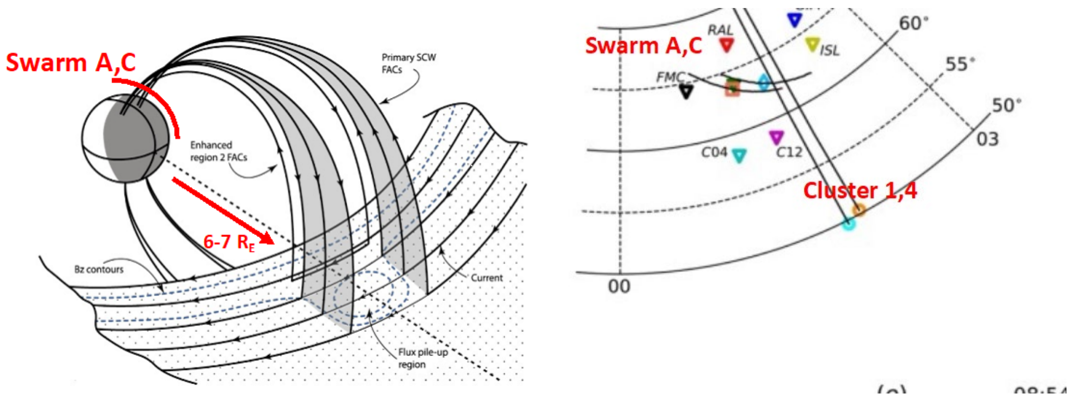

Fig. 1: (Left) Distribution of field-aligned currents in a substorm current wedge on the nightside of the Earth's magnetosphere, showing the orbital positions of the Swarm A, B (red) line, and the distance to the Cluster spacecraft at 6 to 7 R_E. (Right) Cluster and Swarm spacecraft tracks projected on to the ionosphere (only the post-midnight sector is shown between 00 hrs and 03 hrs magnetic local time), plus the position of ground magnetometer stations that detected large changes in the horizontal component of the Earth's magnetic field. Magnetic latitudes marked in degrees.

Jade Reidy (BAS, UK) discussed the phenomena of transpolar arcs (TPAs), that often appear in the polar cap under northward interplanetary conditions. TPAs may be seen in one, or both polar caps, and these arcs are often seen to move, with motion independent between hemispheres. The formation mechanism of TPAs is controversial. Various magnetic field topologies have been suggested, under closed or open magnetic field conditions. Reidy described a large survey of ultraviolet auroral images obtained from the Defence Meteorological Satellite Programme Special Sensor Ultraviolet Spectrographic Imagers, whereby TPAs were identified in one or both hemispheres and the images were compared with in situ measurements along the satellite tracks. It was inferred that those TPAs seen in both hemispheres accompanied by ion precipitation were formed on closed field lines, whereas those TPAs from a single hemisphere accompanied by electron precipitation were formed on open field lines. The formation mechanisms for any exceptions, for example non-conjugate TPAs with no discernible precipitation, is still an open question. However, to resolve this question requires simultaneous observations of both hemisphere, which is not possible with current spacecraft.

Fitting the topic of this RAS Specialist Discussion Meeting very well, Graziella Branduardi-Raymont (MSSL/UCL, UK) presented the first of three missions this meeting. The SMILE (Solar wind Magnetosphere Ionosphere Link Explorer) mission offers a new approach to global monitoring of geospace by imaging the magnetosheath and cusps in X-rays emitted when high charge-state solar wind ions exchange charges with exospheric neutrals. SMILE will help quantify the global effects of the drivers of Sun-Earth connections, monitor their evolution with time and will help validate the models that have been developed to describe these interactions. SMILE is a self-standing mission coupling X-ray imaging of the magnetosheath and polar cusps with simultaneous UV imaging of global auroral distributions and in-situ solar wind/magnetosheath plasma and magnetic field measurements. SMILE will provide scientific data on the solar wind-magnetosphere interaction continuously for long, uninterrupted periods of time from a highly elliptical northern polar orbit which takes it out to 20 Earth's radii apogee (see figure). SMILE is a collaborative mission between ESA and the Chinese Academy of Sciences, currently under development and due for launch at the end of 2024. The presentation covered the novel science that SMILE will deliver and the ongoing scientific and technical preparations for the mission.

Rob Shore (BAS, UK) described the use of a linear machine learning technique (logistic regression) to characterise substorms and sawtooth events, based on 5 years of ground geomagnetic data. Shore showed how a physical interpretation of the model coefficients allows us to discover the ground geomagnetic variations which are associated with the greatest likelihood of event onset. Two distinct substorm onset precursor features are resolved. Firstly, from 45 mins before onset, dayside reconnection is stronger than nightside reconnection (relative to a zero-mean background), consistent with loading of the magnetotail. Secondly, from 20 mins before onset, a convection in the ionospheric equivalent current (centred at local midnight and 73° geomagnetic latitude), reflecting the start of magnetotail dipolarisation which precedes onset. There are no striking morphological differences in these precursor features between sawtooths and substorms. Shore et al. concluded that substorms and sawtooth events have similar initial triggering mechanisms.

Our second invited speaker was David Sibeck (GSFC/NASA), who introduced the Solar-Terrestrial Observer for the Response of the Magnetosphere (STORM) mission. Sibeck began by remembering his friend and colleague, Michael Collier, who had sadly passed away earlier in the week. Michael was a much loved and well-respected scientist, who had championed and been at the forefront global imaging instrument development for many years. He had mentored and inspired many people, through his scientific insights, with unwavering support of colleagues, and kindness. As a community, we feel hugely grateful to Michael and we will endeavour to build on his legacy.
Using a suite of six instruments, STORM will image the magnetosheath, auroral oval, exosphere, and ring current from a highly-inclined circular orbit of 30 RE, and be complimented by in situ measurements. The overarching aim is to quantify the global flow of energy though the coupled solar wind-magnetosphere system on both the day and night side. Ground-based red and green all sky imagers located in North America are integral to STORM's plans. Amongst its goals, STORM will resolve questions about nightside triggers of substorms such as the role of an enhanced ring current, or quantifying gains and losses of the ring current through injections, precipitation, outflows, and charge exchange. STORM will disentangle different transport and loss mechanisms throughout the sub-domains of the global system, and determine their relative contributions under varying interplanetary and solar wind conditions. At the time of the meeting, STORM was in a Phase A study at NASA. Unfortunately, since our meeting, STORM has not been selected to progress. The proposal, ideas, and technology for STORM are mature, and the team will seek a future opportunity.

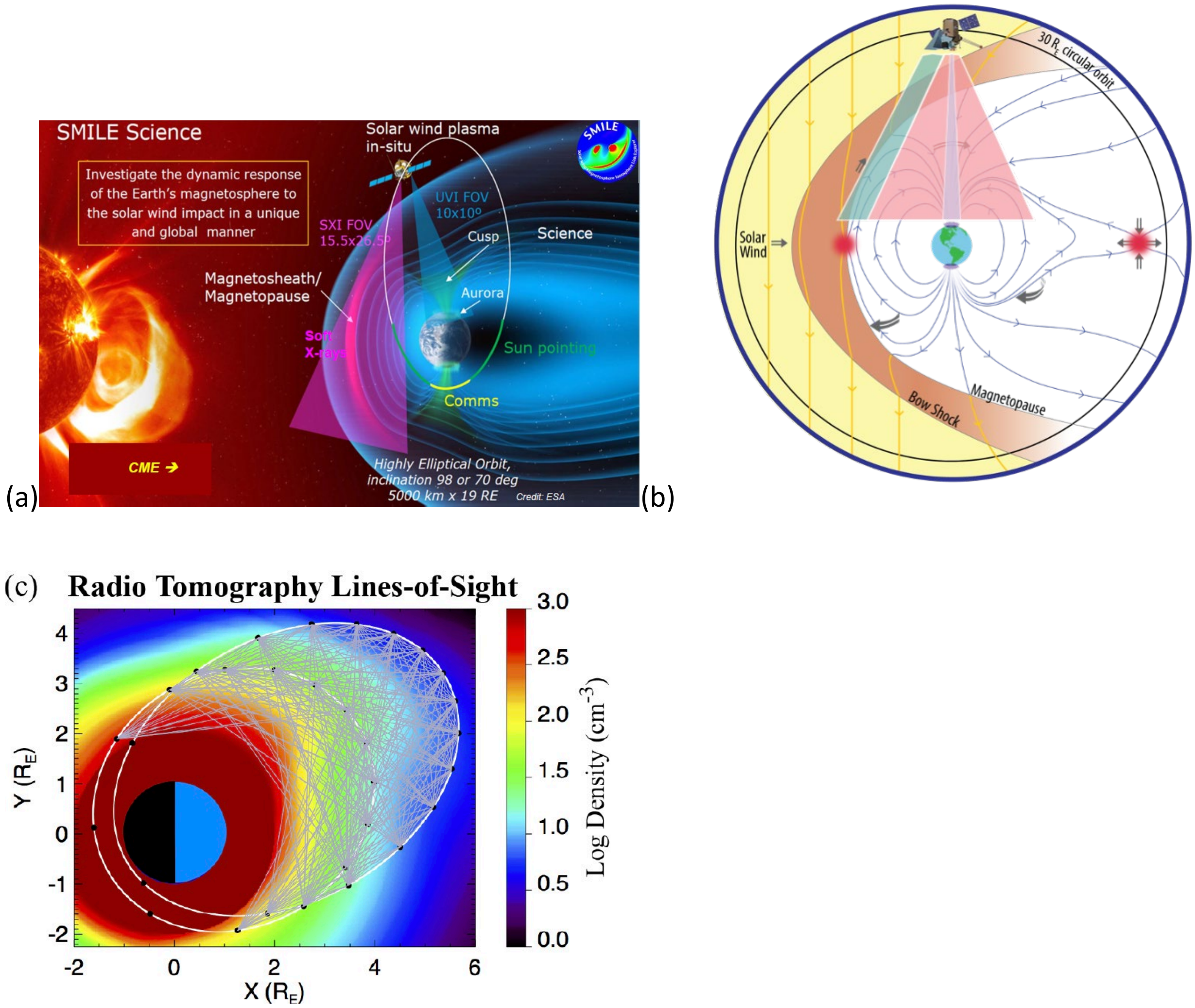

Fig. X: Several missions to monitor global geospacer are either in preparation or under study. (a) SMILE orbital configuration and key science areas, (b) STORM orbital configuration, (c) PILOT example orbital configuration involving multiple satellites, enabling instantaneous tomography.

Matina Gkioulidou (JHU/APL, US) stressed the need to understand mesoscale phenomena, to truly bridge the current knowledge gap between local and global phenomena. The mesoscale can be considered as distances of 1000 km to a few Earth radii in the magnetotail, or between a few 10s to a few 100s of kilometres in the ionosphere. Understanding the contribution of Bursty Bulk Flows and dipolarisation fronts to the build-up of the storm-time ring current through ion injections was cited as an example question where knowledge of the mesoscale is essential. There is currently a disconnect between the dipolarisation fronts predicted in MHD models and the observational evidence obtained by the limited numbers of in situ instruments. Gkioulidou quoted David Sibeck, saying that our current prediction capabilities for understanding ion injections is like "Trying to predict a hurricane using one weather station". Within the ionosphere, we still need to link auroral phenomena to mesoscale magnetospheric processes, to answer questions such as 'Is the substorm current wedge a coherent structure or made up of wedgelets?' (see Fig. 3, b), 'How do auroral streamers evolve?', 'What causes an auroral arc?', or 'How much does mesoscale precipitation contribute to the total energy flux deposited in the ionosphere?'. Gkioulidou finished with a positive message that the next decade will likely see a shift change in the understanding of mesoscale processes. She also cautioned that next generation concepts that include imagers (e.g. SMILE and STORM), would need simultaneous in-situ instruments on separate spacecraft platforms to make plasma measurements within the regions of the phenomena being imaged.

Fig. 3: We need to understand how to link global to local phenomena, by increasing our understanding of mesoscale processes. The images show a schematic of a substorm current wedge either as (a) one coherent large-scale structure, or (b) made up of multiple wedgelets. Figure reproduced from Nishimura et al. 2020. [Figure requested]

Nithin Sivadas (NASA/GSFC, The Catholic University of America) spoke about the importance of understanding uncertainties in solar wind propagation from the upstream L1 point for geospace studies. We often look for associations between solar wind forcing of the magnetosphere. The solar wind electric field drives reconnection leading to ionospheric convection, which can be monitored via changes in the polar cap potential. Previous statistical studies have suggested that the polar cap potential increases linearly with increased solar wind driving, however, when the electric field is high, the polar cap potential is seen to saturate. There is no clear consensus as to why this saturation would occur. The saturation effect may only be a perception, due to uncertainties in solar wind propagation. Solar wind measurements are taken at L1, at 230 RE upstream of the magnetic reconnection site. The interplanetary magnetic field can also rotate up to 30 deg. when traversing the magnetosheath. Using a regression calibration technique, Sivadas et al. show that the random error in solar wind measurements may be sufficient to explain the non-linear response of the polar cap potential.

Energetic neutral atom (ENA) emissions give us a useful view of the global structure of the ring current and near-Earth plasma sheet, and an opportunity to study mesoscale structures. Natalia Buzulukova (NASA GSFC/UMCP) showed observations of O+ emissions as they change over the course of a substorm, including a bright spot of emission which was modelled and then interpreted as an example of ion injection, see Fig. 4. Observed post-midnight enhancements in ENA emissions were shown, which could only be modelled using an MHD simulation including a self-consistent electric field describing ring current feedback. Buzulukova described the technical challenges facing ENA imaging, including extending the energy range of major species (H+, O+) and improving the resolution down to mesoscale structures.

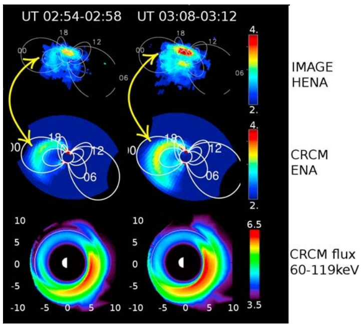

Fig. 4: ENA imaging and modeling of a substorm injection during 12 August 2000. From top to bottom: IMAGE HENA integrated H ENA flux (/sm^2/sr/s); simulated H ENA flux (/sm^2/sr/s); modeled equatorial H+ differential flux 60-119 keV used to produce

David Malaspina (University of Colorado, Boulder, US) presented a novel space mission concept: PILOT, the Plasma Imaging, LOcal measurement, and Tomographic experiment that will be presented to the upcoming NASA Decadal Survey. PILOT traces the flow of plasma mass and energy through geospace by combining global meridional imaging of cold plasma with meso-scale equatorial radio tomographic imaging of plasma density and embedded in-situ probes. A particular science question to address will be to ask 'How is the atmosphere of a magnetised planet like Earth lost to space?' Malaspina stressed that there are still many unknowns in our understanding of how mass is transported around the magnetosphere and how this mass flow regulates magnetosphere subsystems. An example would be the plasma plume that occasionally extends outwards from the plasmasphere up to the magnetopause – we know it exists, but the formation processes and what drives any wrapping around or evolution of the plume remain elusive. A second example would be to quantify O+ ion outflow from the ionosphere in relation to magnetospheric refill rates and to understand how these ions become trapped in the plasmasphere. The PILOT mission concept involves 30 micro- and small satellites to provide instantaneous radio tomography, supported by EUV images of He+ and O+ distributions in the plasmasphere, and is highly complementary to a range of current and planned geospace observations, see Fig 2, c.

Eric Donovan (University of Calgary, Canada) finished the meeting by emphasising how space and ground-based experimentation must be used simultaneously to understand the magnetosphere at multiple scales. He introduced the SMILE All Sky Imager (ASI) network. This network of red and green line cameras across Canada will be a modification and replacement of the ageing technology of the white-light THEMIS ASI network that has been operational since 2006, and which has been exposed to the harsh conditions in the tundra since then. The SMILE Ultraviolet Imager will provide global coverage of the Northern Hemisphere auroral oval at low (~100 km) spatial resolution and moderate time resolution (1 minute), whereas the ASIs provide excellent spatial and temporal resolutions at kilometre and a few second-scales. This resolution is more than adequate for the auroral arcs used to investigate magnetospheric processes (Knudsen et al. 2001). The extent of the new network has a wide local time and latitudinal spread, which can encompass the whole substorm onset and evolution of the substorm auroral oval bulge. The new network extends further into the polar cap than THEMIS-ASI to capture high-latitude, although without the farthest East-West extent in Alaska and Greenland, which has shown to be of much benefit. The two-colour system allows the determination of both faint aurora, and the auroral oval boundary at a few kilometre resolution, that can be later be used for calibration of images from the wide-band SMILE Ultraviolet Imager, and an excellent chance to capture the attention of the general public.

We enjoyed a poster session using the free Wonder Space platform. Poster presenters provided a 1-minute lightning talk to advertise their poster and highlight the key points of their study.

Joe Eggington (Imperial College London) presented the results of the September 2017 geomagnetic storm using an operational version of the Gorgon magnetohydrodynamic (MHD) which is currently under development. The study compares the results of the simulated ionospheric conditions and ground magnetic field data against SuperDARN and auroral index data. Eggington et al. found that the model predicted similar trends in the cross polar cap potential compared to observational data from SuperDARN but that the model slightly over-estimated the cross polar cap potential. The model also performed well at modelling the first phase of the storm, however this was reduced during the second phase due to significant substorm activity during this period. Eggington et al. concluded that the Gorgon MHD code is capable of the real-time prediction of space weather metrics but that more accurate auroral and night-time conductances would help.

Elwina Florczak (University of Edinburgh, British Geological Survey) investigated the performance of 4 MHD models and their ability to predict the ground magnetic field components measured during the September 2017 geomagnetic storm. The MHD models evaluated were the Space Weather Modelling Framework (SWMF), the SWMF coupled with the Rice Convection Model, the Grand Unified Magnetosphere-Ionosphere Coupling Simulation (GUMICS) and the Gorgon model. Florczak et al. compared the model performance of each of the models against observations of the northward (B_X), eastward (B_Y) and horizontal (H) components of the ground magnetic field measured at 3 locations around the UK; at Lerwick, Eskdalemuir and Hartland. Florczak et al. found that the accuracy of each model varied with time, location and the component of the ground magnetic field (B_X, B_Y, H) being examined and the most suitable model would depend on the end user requirements. Model to observations discrepancies may include timing errors from using simplified solar wind inputs, the inability of models to accurately represent substorm characteristics and the shift in location of the electrojets in the simulated magnetospheric and ionospheric currents.

Andrey Samsonov (Mullard Space Science Laboratory, University College London) studied solar wind charge exchange between heavy highly charged solar wind ions and exospheric neutrals produces soft X-rays in the geospace. The Soft X-ray Imager (SXI) on board the forthcoming SMILE mission will measure X-ray emissivity integrated along the Line-of-Sight (LOS). By analyzing 2-D maps of X-ray counts, we can extract information about magnetopause shape and position. It has been suggested that the maximum of integrated emissivity is tangent to the magnetopause. This assumption is checked using the results of

MHD simulations for different points along the SMILE trajectory. The assumption that the maximum integrated emissivity is tangent to the magnetopause is generally found to be reasonable, although the maximum of the integrated along LOS emissivity may be slightly farther from the Earth.

Ravindra Desai (Imperial College London) investigated the interaction between coronal mass ejections (CMEs) to create the perfect storm in geospace. Using a spheromak CME approximation within a representative 3D heliospheric MHD model, Desai et al. parametrically assess 3 quantities including the initial tilt angle, the waiting time between two CMEs and the CME handedness or chirality to investigate what CME-CME interactions produce the most extreme conditions at 1AU. Desai et al. found that two moderate CMEs can produce an extreme event at 1 AU. In addition, Desai et al. also found that the handedness/chirality of a CME can have a major influence on the geoeffectiveness of CME-CME interactions due to prolonged conservation of toroidal flux, as a certain handedness/chirality of CME can either induce or supress magnetic reconnection which can have a major influence on the predicted disturbance storm time (DST) index.

John Coxon (Northumbria University) examined distributions of Birkeland currents observed by the Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) between 2010–2012. Coxon showed that these distributions are heavier-tailed than a Gaussian distribution (leptokurtic), and in some cases heavier-tailed than an exponential distribution. He exploited the survival function in order to derive the probability of seeing extreme current densities (current densities with a magnitude above 4.0 μA m-2) and plotted these probabilities on maps of the Northern and Southern Hemispheres; shown in Figure X. This shows that the probability of extreme current flows is highest at ~20° colatitude on the dayside, and also shows that extreme currents are ~7 times more likely in the Northern Hemisphere than in the Southern Hemisphere.

Daniel Billett (University of Saskatchewan) presented a newly derived database of hemispheric Poynting flux patterns using the overlapping SuperDARN and AMPERE campaigns, see Fig. 5. An initial statistical study from this new data product shows that the large-scale (100s of kilometres) Poynting flux can't fully account for thermospheric density perturbations often seen near the cusp. However, high-resolution and sub-kilometre scale measurements, recently processed from the Swarm constellation of satellites, show that as much as 50% of the integrated Poynting flux is lost when low-pass filtering up to SuperDARN/AMPERE scale sizes. These findings stress the importance of very small-scale electric field variability in the determination of the Magnetosphere-Ionosphere energy budget.

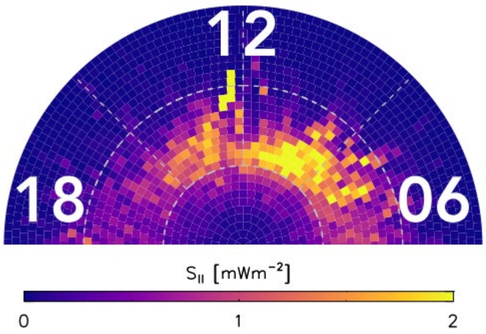

Fig. 5: Statistically averaged dayside Poynting flux from the Swarm A satellite under northward interplanetary magnetic field conditions.

Amy Keesee (University of New Hampshire) described how energetic neutral atom imaging can provide a global view of the magnetosphere, providing information about the connection from the magnetotail to the inner magnetosphere. In a study of a storm-time substorm interval, the observed plasma heating is less intense in the simulated results than in the TWINS and MMS data, indicating that some heating processes may be missing from the model (Keesee et al, 2021). An automated detection algorithm currently being validated will help with identifying more interesting events for case studies as well as conducting statistical analyses of the regions of enhanced ion temperatures. An ENA imager would also make a useful space weather monitor, given the necessary time resolution, processing, and downlink to provide a forecast.

Brian Walsh (Boston University) presented the Lunar Environment heliophysics X-ray Imager (LEXI), a lunar surface telescope which will image Earth's dayside magnetopause location and shape to understand the macroscale solar wind-magnetosphere coupling and the properties of dayside magnetic reconnection. In particular, LEXI hopes to understand under what conditions magnetopause reconnection is steady or bursty. LEXI utilises micropore optics to focus soft X-rays in the range of 0.1 – 2 keV over a wide field of view (9.1° x 9.1°). LEXI is scheduled to land on the lunar surface in 2023 and will be operational for 1 week.

The presentations during this meeting set the scene of current global system-level geospace science. The studies presented covered a wide range of spatial and temporal scales and utilising ground and space-based observations, in conjunction with state-of-the-art modelling, providing a global view of magnetospheric dynamics. During the meeting, it was highlighted that areas for future improvements should be directed into modelling for space weather applications including data assimilation techniques and model validation as well as the use and development of new data analysis techniques such as machine learning methods. Presenters also highlighted the significance in understanding meso-scale processes with upcoming opportunities for multi-spacecraft coordinated activities, combining remote, in-situ and ground based observations as well as opportunities for simultaneous observations of the northern and southern aurora.

The success of upcoming missions including SMILE and LEXI as well as mission concepts such as PILOT, STORM, and those exploring ENA imaging demonstrate the health of geospace research and will provide many new observational datasets and present opportunities for multi-observation coordinated studies, interhemispheric studies, and exciting new science.

This meeting has strengthened the idea that global monitoring of geospace, combined with embedded in-situ observations, is crucial in making the next big leap in magnetospheric physics: determining how the exchange of mass and energy among magnetospheric subsystems enables their cohesive response to solar wind driving. The novel missions that are either due to launch, or are in planning will make major steps forward in understanding geospace at the system scale. We thank all presenters and participants for a fantastic and productive day.

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Author bios

Jenny Carter is a Royal Society Dorothy Hodgkin Research Fellow at the University of Leicester. She is also the chair of the SMILE Ground-based and Additional Science working group.

Maria Walach is a post-doctoral research associate at Lancaster University, working on validating a time-variable ionospheric electric field model using SuperDARN in the context of whole atmosphere modelling.
Michaela Mooney is a post-doctoral research associate at the Mullard Space Science Laboratory, UCL.