The Global Response of the Terrestrial Magnetosphere during Storms and Substorms

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The History of Magnetospheric Science

Explorations into the geomagnetic field are thought to have originated around the beginning of the 11th century in China, later extending to Asia and Europe [Mitchell, 1932], and leading to the discovery of the global nature of the magnetic field reported in “De Magnete” [Gilbert, 1600]. Since then, we have identified the highly variable and dynamic nature of the global geomagnetic field in near-Earth space, specifically the discovery of magnetic storms and substorms [e.g., Graham, 1724; Birkeland, 1901]. Based only on ground observations, key features of our space environment were proposed: the ring current [Stoermer, 1910], the plasma-filled magnetosphere [Gold, 1959; Chapman and Ferraro, 1931], and the solar wind [Parker, 1958]. These were all later confirmed with the advent of the Space Age, as well as the discovery of new features, such as our highly dynamic radiation belts [Van Allen, 1958].

In 1961, Jim Dungey proposed a new theory regarding how our magnetosphere interacts with the solar wind [Dungey, 1961] to explain the observed dependence of geomagnetic activity on solar activity [e.g., Sabine, 1852]. Dungey [1961] proposed the idea of an “open magnetosphere”, where coupling between the geomagnetic field and the Interplanetary Magnetic Field (IMF) leads to a large-scale, global, circulatory flow of magnetic field lines and plasma within the magnetosphere. This theory was later confirmed observationally [Fairfield et al., 1966; Fairfield, 1967], and we now know that the coupling between the solar wind and the magnetosphere creates a dynamical and highly variable system, and is a key driver in generating storms and substorms. A simplified schematic of our current understanding of the magnetosphere, and the key regions of interest, is illustrated in Figure 1.

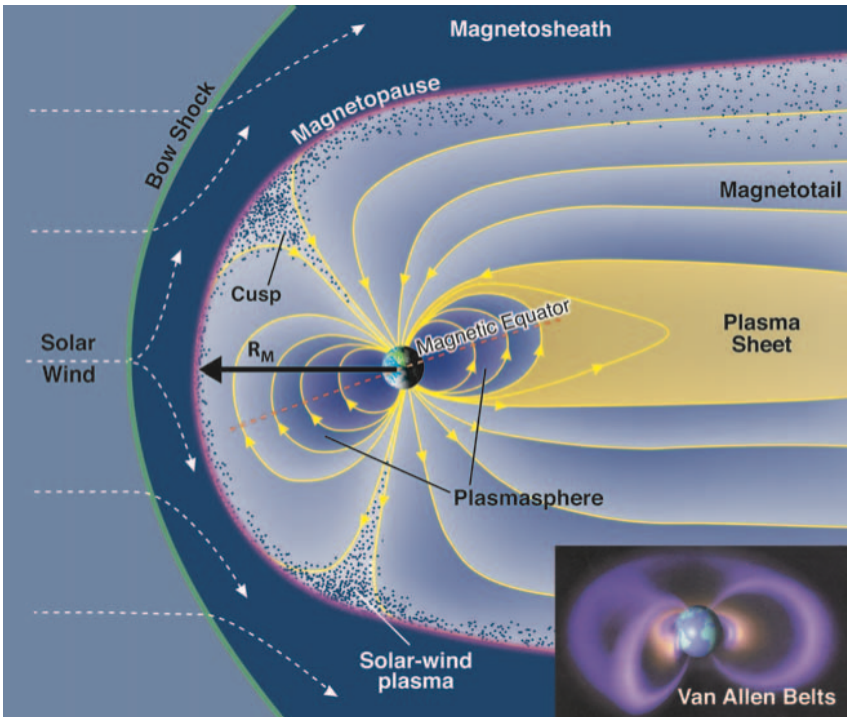

Figure 1: A schematic illustrating the large scale structure of the magnetosphere and the key regions. The inset shows the structure of a trapped energetic particle population in the inner magnetosphere, known as the Van Allen radiation belts. [Kivelson and Bagenal, 2007]

Background and Motivation

The RAS recently hosted a Discussion Meeting on the global response of Earth's magnetic environment to storms and substorms. In this article, we review current knowledge and future directions.

Storms are characterised by rapid enhancements in the ring current, an electrical current in the inner magnetosphere produced by the net westward drift of ions, where increases in the energy and number of ions results in increases in the ring current intensity. During magnetic storms, large enhancements in the ring current intensity lead to a weakening of the local magnetic field and are also associated with intense radiation belt activity [Gonzalez et al., 1994, Baker et al., 2004]. On average, storms have a duration of several days, with the storm main phase lasting around 1 day. Geomagnetic storms are observed to be highly variable in terms of their intensity, duration, and impacts on the inner magnetosphere. A key impact of geomagnetic storms is concurrent radiation belt activity in the inner magnetosphere. The radiation belts have a complex relationship with geomagnetic storms, and also exhibit a high degree of variability, shaped by the multitude of energisation and loss processes [e.g., Elkington, 2013, Reeves et al., 2003].

In contrast to storms, substorms have timescales of a few hours. Substorms are characterised by a storage and rapid release of energy by the magnetotail, and are associated with clear auroral signatures and intensifications [e.g., Baker et al., 1981]. Strong coupling with the IMF leads to a loading of highly stretched open field lines to the magnetotail. The triggering of substorm onset is accompanied by rapid magnetic reconnection in the magnetotail and promptly closes large amounts of flux. The stretched field lines contract to a more dipolar configuration, a considerable amount of energy is released, and highly energetic plasma is transported earthwards on the nightside. Intense field-aligned currents drive energetic electron precipitation and result in the intensification, broadening, and expansion of the auroral oval (see Figure 2). Although it is known that substorms occur during times when the magnetosphere is effectively coupled with the IMF, substorms are highly variable and unpredictable in nature. Furthermore, due to the ability of substorms to transport energetic plasma to the inner magnetosphere, it has been proposed that substorms are important in generating geomagnetic storms [Daglis et al., 1999a,b]. However, the role of substorms in storm generation has also been debated by others [Kamide, 1979, 1992], and the coupling between substorms and storms remains unclear.

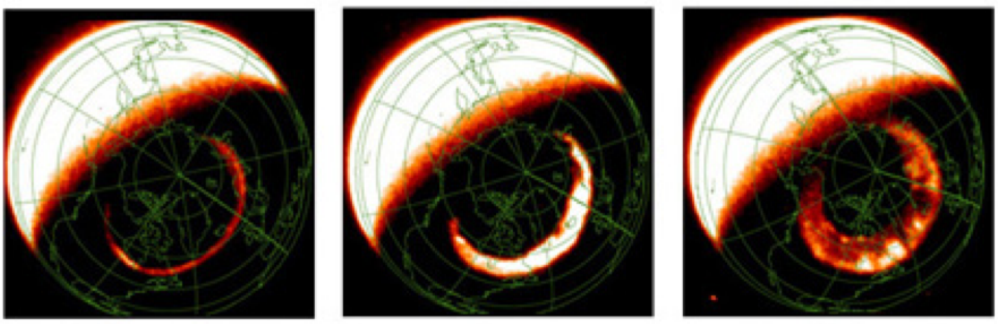

Figure 2: The northern auroral oval viewed by the IMAGE spacecraft. The thickening and contraction of the auroral oval following substorm onset is apparent. (Image credit: SWRI)

Due to the induced currents and magnetic field perturbations, the occurrence of a storm or substorm can be identified from magnetic field observations at the ground. Magnetic field data can be condensed into simple indices that exhibit relatively clear signatures during storms and substorms, and are highly useful in identifying and exploring events (see box for further details).

Studies of the magnetosphere, specifically the storm and substorm phenomena, are strongly motivated by the implications of these processes on our everyday lives. Although very intense storms and substorms are rare, when they do occur, the ramifications are significant [Lanzerotti, 2013]. The events drive large Ground Induced Currents (GICs), which can disrupt ground power networks. Changes to the ionosphere can lead to radio wave absorption and thus communication black-outs. Additionally, geomagnetic storms can have devastating effects for satellites: extreme intensifications of the radiation belt are highly damaging to satellites, and an altitudinal increase in the ionospheric boundary during storms increases satellite drag for low-orbiting satellites. Therefore, understanding the physical processes associated with storms and substorms, determining why they occur, and identifying how they affect our magnetosphere are factors that we need to consider. There are many outstanding questions surrounding this area, and much remains to be investigated. This was the motivation for holding an RAS Specialist Discussion meeting, where work on understanding storms and substorms was presented and discussed. In this review, we explore the key questions that were raised in the context of existing understanding, the new results presented, and the discussions which were had.

How important is variability?

A key discussion topic that arose in the meeting concerned how we extract information regarding physical processes from trends in magnetic indices. Storms and substorms are highly variable processes, and events that reach the same magnitude in a given index can differ greatly in other observed characteristics. For example, two substorms may be associated with the same AL index minimum, but the duration of the bay, the auroral signatures of the substorm, and the impacts on the inner magnetosphere can vary significantly between the two events. The use of a single index at a single time represents the globally averaged magnetic field response, and is unable to capture the large degree of variability in other aspects of the magnetosphere (e.g. solar wind driving and plasma properties). Conversely, taking events which seemingly have the same level of solar wind coupling and internal conditions, the response of the magnetic indices and the magnetospheric system is wide ranging, in terms of the occurrence and intensity of storms and substorms, as well as steady magnetospheric convection.

A fundamental question is why do we observe so much variability? And what physical magnetospheric processes are driving this variability? An insightful comment by Sarah Bentley (University of Reading) highlighted that it is important to review how we consider the magnetospheric system. Taking a deterministic approach, there must be a process in the magnetosphere or a characteristic of the solar wind coupling that we haven't identified. Or, alternatively, is it just the chaotic nature of the system that introduces this variability [e.g., Prabin Devi, 2013]? This brings to light the question of whether we are actually able to predict when and how these events occur, and identify the source of the observed variations.

In contrast to the seemingly unpredictable qualities of the magnetosphere, work presented by Sandra C. Chapman (University of Warwick) demonstrated clear reproducible trends in the distribution tails of magnetic indices (including the AA index, Dst index, and AE index), over several solar cycles [Chapman et al., 2018.] Chapman highlighted that this result was derived from the data only, without any restrictions based on knowledge of physical processes and despite each solar cycle varying in duration and peak activity level. By extrapolating this trend, the promising potential for predicting super-storms for space weather climatology was highlighted and explored by Aisling Bergin (University of Warwick). The reproducibility aspect of extreme storm occurrence provides an avenue into understanding variability in storms. Furthermore, Heather McCreadie (University of Warwick) demonstrated how the variations in the Dst index during any storm can be characterised using an autonomous curve fitting technique. McCreadie's approach in quantifying the Dst index variations during storm suggests important applications in being able to explore variability in the Dst response from storm to storm.

How do we define storms and substorms?

The discussion on how events characterised by the same level of magnetic indices led to thoughts on what information on physical processes are provided by the indices. Is this the information that we need? And if not, what is required and how does that influence how we define these events?

As discussed above, storms and substorms exhibit a high degree of variability associated with different features of the event (e.g. solar wind coupling, magnetic responses, inner magnetospheric response etc.). In order to identify how we define the events, a choice has to be made on what is the defining feature of interest. The meeting highlighted that the important feature of a storm or substorm is highly dependent on the "end user", as pointed out by Chapman in the discussion. For example, Richard Horne (British Antarctic Survey) discussed how storms driven by a Coronal Mass Ejections (CMEs) are associated with a much larger ring current enhancement and magnetospheric compressions than storms driven by Corotating Interaction Regions (CIRs), and as such, are able to generate intense GICs. In contrast, the CME-driven storms are associated with a significant inward transport of the radiation belts, unlike the CIR-driven storms, such that geosynchronous satellites are no longer situated within the radiation belts during CME-driven storms but they are located within the radiation belts for CIR-driven storms. Consequently, CIR-driven storms pose a significant hazard for space-based instrumentation and CME-driven storms pose a significant hazard for ground electrical networks [Borovsky and Denton, 2006]. This example highlights the difficulty in identifying what is the crucial feature of the storm, due to the dependence on the "end user" needs.

The "end user" problem also has implications for what we consider to be "big" or "small" events. Many storms and substorms are categorised by the ring current and auroral electrojet indices, respectively, only considering events that are above a certain threshold and attributing the size to the peak magnitude of the index. We know that the magnetic indices only describe one part of the system, and can conceal a wealth of information. The keynote talk by Elena Kronberg (Max Planck Institute for Solar System Research) highlighted the broad and significant implications of magnetospheric composition, and how the presence of heavy ions during storms and substorms plays an important role in shaping the events. Particularly, the presence of heavy ions can be an important contributor to the total ring current energy [Kronberg et al., 2017]. Alternatively, the radiation belts are also a key component of magnetospheric dynamics and work by Colin Forsyth (MSSL, UCL), for example, demonstrates the different degree of radiation belt enhancements due to the substorm process. In contrast, GICs have been demonstrated to be significant during storms and substorms, as highlighted by Neil Rogers (Lancaster University) who examined drivers of these extreme magnetic field fluctuations. Overall, it is clear that it is difficult to assess the size of a storm or substorm, without first prioritising whether the "end user" is most interested in ion composition, radiation belt enhancements, GICs, radio wave absorption in the ionosphere etc.

The application of a threshold for defining storms and substorms using magnetic indices also highlights some key issues. The threshold is often chosen to distinguish clear events from background fluctuations in the indices. Although this is a reasonable and practical option, it inherently neglects the smallest events, and prohibits our understanding of how storms and substorms vary across all magnitudes. We do not yet have a clear understanding of how small a storm or substorm can be. This highlights a significant lack of knowledge of what a storm or substorm actually is, and current methods simply define the events as a deviation from background variations in a magnetic index. Improvements on defining the events then rely on understanding the key physical processes: what triggers the events and why?

Why do substorms occur?

Presentations at the meeting showcased the breadth of work being conducted to understand why storms and substorms occur. The results provided significant insight into determining the conditions under which the events occur and how these conditions shape the type of activity.

Current literature presents a divided view on substorm initiation, largely focusing on two key theories. The Near-Earth Neutral Line (NENL) model proposes the formation of a neutral line in the magnetotail at approximately 25 Earth Radii (RE) [Baker et al., 1996]. The loading of the magnetotail with open flux during the substorm growth phase results in the thinning of the tail current sheet, and continues until a threshold is reached. Magnetic reconnection of the tail field lines is triggered at the neutral line and the dipolarisation of field lines and current divergence along the field lines ensues. The NENL model is commonly referred to as the "outside - in model", as the disturbance originates in the tail due to reconnection and initiates the current disruption closer to the Earth at approximately 10 RE. Conversely, the cross-field Current Disruption (CD) model has also been proposed to explain the substorm initiation process [Lui, 2015]. The CD model suggests that plasma instabilities in the near-Earth region act to disrupt the current sheet and consequently trigger reconnection of field lines downtail. This is known as the "inside – out model". Present understanding of substorm initiation is unclear on when either the NENL model of CD model is applicable, and no consensus has been reached. However, this meeting included work that indicates progress in unravelling the substorm initiation process. The meeting included a presentation from John Coxon (University of Southampton), who investigated energy propagation through the magnetotail during the substorm process. Using Cluster observations of the magnetospheric lobes, Coxon demonstrates that following substorm onset, energy density signatures are first observed in the near-Earth magnetotail and then propagate downtail on timescales of approximately 20 minutes (Figure 3) [Coxon et al., 2018]. The results suggest that substorms are triggered in the near-Earth magnetosphere with the disturbance propagating downtail, in accordance with the CD model. Furthermore, work presented by Andy Smith (MSSL, UCL) also investigated the substorm initiation process using in situ observations. Smith utilised THEMIS observations to understand the characteristics of plasma instability-driven waves associated with the substorm onset process [Kalmoni et al., 2018]. Smith's work presents a promising avenue into understanding how and when near-Earth plasma instabilities are responsible for substorm initiation.

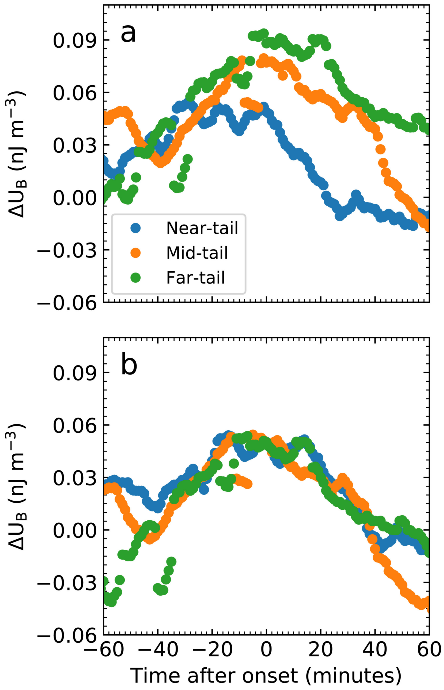

Figure 3: (a) Variations in the energy density, binned for downtail distance in the magnetotail, and plotted relative to substorm onset. The signatures are first seen in the near-tail, and seen latest in the far-tail suggesting that the disturbance propagates tailwards. (b) The data shown in (a) are time lagged so that the plateaus centre on substorm onset. (Coxon et al., 2018)

As well as understanding how substorms are triggered, another key area of active research includes understanding why different types of substorms are observed and the drivers of these events. One type of substorm activity is periodic substorms, also known as sawtooth events. Sawtooth events are sharp enhancements and slow decays of energetic particle fluxes in the inner magnetosphere occurring periodically with a consistent periodicity of approximately 3 hours [e.g., Borovsky et al., 1993]. The events are associated with dispersionless injection events driven by magnetospheric dipolarisation, attributed to the occurrence of substorms [e.g., Huang et al., 2003]. Kronberg referred to periodic substorm-like events observed at Jupiter, which are tail reconnection events accompanied by auroral activity and periodic energetic flux dropouts, and have a periodicity of approximately 3 days [Radioti et al., 2008]. These events are thought to be internally driven, primarily due to internal magnetospheric mass loading from Io's plasma outflows. The relatively constant rate of mass loading imparts an approximately stable periodicity to the field line stretching and consequent tail reconnection [Vasyliunas, 1983]. Kronberg then related this to a similar process occurring within the terrestrial magnetosphere. It is proposed that relatively constant plasmaspheric mass loading from auroral outflows effects the magnetosphere in a similar way to Io's outflows at Jupiter. The internal mass loading leads to field line stretching and drives periodic substorms, resulting in the occurrence of sawtooth events (Figure 4) [Kronberg et al., 2008]. Kronberg emphasised the need for observational studies to investigate the role of internal mass loading further, and the discussion highlights a key area of future research.

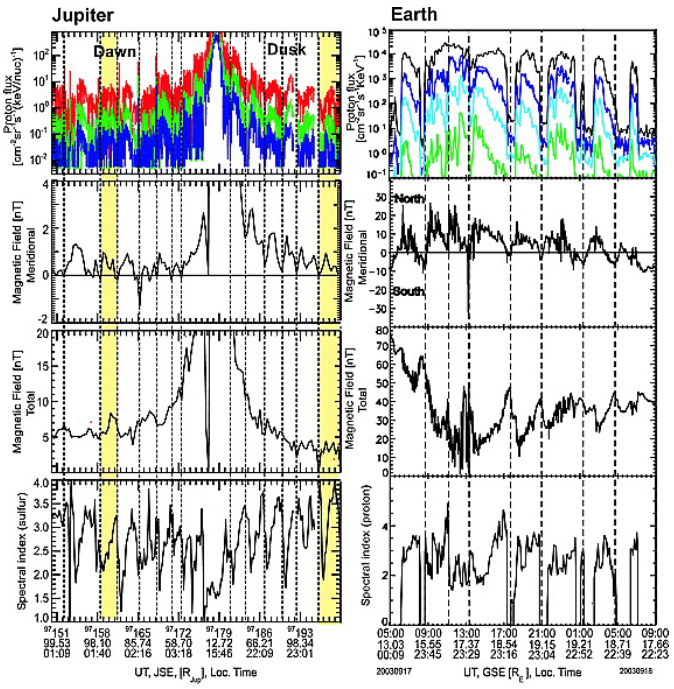

Figure 4: A comparison of proton flux (first panel), magnetic field (second and third panels), and energy spectral index (fourth panel) during sawtooth events at Jupiter (left) and Earth (right). Periodic loading and field stretching is observed for both systems, with the times of dipolarizations indicated by the vertical dashed lines. (Kronberg et al., 2008).

Work by Steve Milan (University of Leicester) highlighted that substorm activity can be categorised by the auroral onset latitude and suggested two distinct types of substorm activity: substorms associated with high-latitude onsets and substorms associated with low latitude onsets. Previous work has demonstrated that this distinction is associated with a range of differences, such as the ionospheric convection [Grocott et al., 2009], auroral intensity, and inner magnetospheric conditions [Milan, 2009]. Milan demonstrated a further key difference, namely that substorms associated with a high latitude onset and prolonged dayside driving are likely to be followed by a period of Steady Magnetospheric Convection (SMC), in agreement with the results of Walach and Milan [2015]. In contrast, substorms with a low latitude onset are more likely to exhibit multiple onsets, such as sawtooth events, as opposed to an SMC. Milan attributed this feature to the characteristics of the ionosphere and its significant role in the coupling process. It was proposed that enhanced ionospheric conductance in the auroral bulge for low latitude substorms inhibits convection, leading to an accumulation of flux and a reduction in nightside reconnection. This prevents occurrence of an SMC, and instead allows the magnetosphere to enter the loading phase of a subsequent substorm.

Understanding the conditions under which substorms occur and the drivers of the activity provides valuable insight into how we can forecast and predict the occurrence of a substorm [Eastwood et al., 2017]. A comment by Horne highlights how our understanding of the conditions prior to substorms can be highly useful in forecasting techniques. Horne discussed that it may be more feasible to predict these conditions, that are probably associated with substorms, than predict the substorm occurrence itself. For example, work by Robert Shore (British Antarctic Survey) demonstrated how, using a machine learning approach applied to ground magnetometer data, clear and distinct signatures are associated with sawtooth and substorm events. Shore identified that although the precursor signatures of sawtooth compared to substorms events differ in magnitude, the structure is essentially the same. Furthermore, Maria-Theresia Walach (Lancaster University) presented an analysis of ionospheric convection observations from the Super Dual Auroral Radar Network (SuperDARN) and showed clear dependences and features associated with solar wind driving and geomagnetic events. These results demonstrate how consistent signatures can be identified routinely that can be incorporated into forecasting techniques, as well as the need for ionospheric observations at mid-latitudes due to the convection pattern expanding.

Work by Micheala Mooney (MSSL, UCL) presented some insight into the current capabilities of forecasting. Mooney assessed the performance of the OVATION Prime-2013 model, which forecasts the probability of observing auroral precipitation in the polar regions [Newell et al., 2014]. They determined that, although the OVATION model performs well at distinguishing the spatial characteristics of aurora occurrence, the probabilities of aurora occurrence are largely under-predicted by the model. An advanced understanding of how the magnetosphere couples with the solar wind and generate aurora is needed to shed light on how we can better forecast auroral precipitation. This example demonstrates that current endeavours into forecasting space weather are significant, but continued investigation into understanding the conditions associated with geomagnetic events are invaluable in furthering progress.

The Importance of Solar Wind Drivers

As well as investigating the magnetospheric conditions associated with substorms, it is essential to understand the key driver of activity: the solar wind. Intensive efforts in examining the solar wind properties and how the solar wind couples to our terrestrial magnetosphere were discussed. Of particular interest were results presented by Téo Bloch (University of Reading), where a new solar wind classification scheme based on machine learning techniques identifies periods of coronal hole wind and streamer belt wind. Previous work has shown that the magnetosphere response varies significantly between these two drivers [e.g., Borovsky and Denton, 2006], so having the capability to categorise the type of driving is essential information. Furthermore, an automated technique suggests significant applications for forecasting methods.

Another important form of variability in the solar wind occurs on solar wind cycle timescales, as highlighted in a comment by Chapman. The solar wind cycle imparts long term variations in geomagnetic activity [e.g., Richardson and Cane, 2012], and thus it is important to consider these trends. For example, Andrei Samsonov (MSSL, UCL) assessed the long term variations in the magnetopause position, as well as the level of geomagnetic activity. In particular, differences between solar cycles can have marked differences in the magnetopause standoff distance. Samsonov reports that the magnetopause standoff distance increased by more than 2 RE for one solar cycle compared to the next, due to long term trends in solar activity.

Understanding the details of how the magnetosphere couples to the solar wind is non-trivial. However, Joseph Eggington (Imperial College London) demonstrated the significant ability of Magnetohydrodynamical (MHD) modelling to investigate the relationship. Using the Gorgon MHD code [Ciardi et al., 2007], Eggington reproduced the coupling between the solar wind and the magnetosphere, identifying the locations of reconnection (Figure 5). This information on where and when reconnection happens is crucial in understanding how energy and flux can propagate through the magnetospheric system. Specifically, it provides details on how flux can be added to the magnetotail during substorm growth phases, where the flux is closed on the nightside, and when the flux closure occurs allowing energy to propagate to the inner magnetosphere.

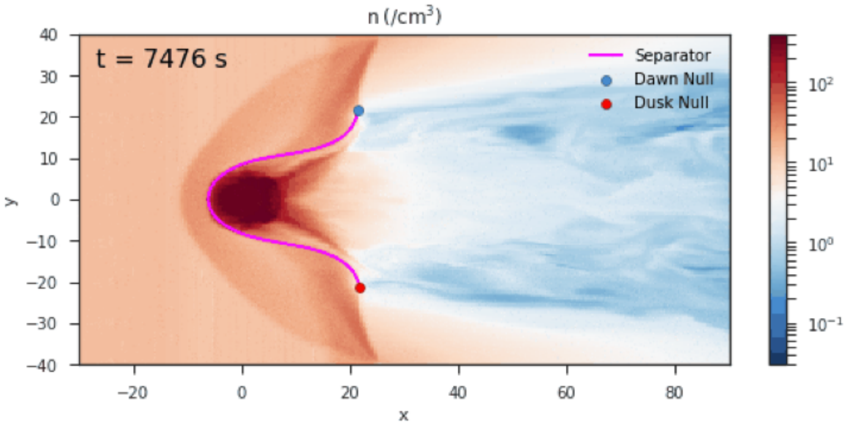

Figure 5: A Gorgon MHD model simulation of a CME shock front distorting the dayside separatrix (pink line), where the background colours indicate the plasma density. (Eggington)

The solar wind – magnetosphere coupling is a primary factor in driving heavy ion outflows from the high latitude ionosphere, which can then be convected throughout the magnetosphere [e.g., Yau and André, 1997]. As highlighted by Kronberg, the presence of heavy ions in the magnetospheric plasma can dramatically alter the dynamics of the magnetosphere. For example, Oullette et al. [2013] show that heavy ion outflows can significantly alter the mass density and pressure in the magnetotail, leading to the formation of a new neutral line for reconnection to occur. Furthermore, heavy ion concentration in the inner magnetosphere is a key factor in the local plasma mass density, thus controlling the Alfvén speed and how energy propagates through the system [e.g., Sandhu et al., 2017, 2018a].

The importance of the inner magnetosphere during substorms

Substorms are associated with a major redistribution of energy within the magnetosphere, and understanding how this energy is partitioned is a key outstanding question. Specifically, understanding whether the substorm process can provide the inner magnetosphere with energetic particles and generate geomagnetic storms, and whether the injected particles can provide a seed population for radiation belt energisation are vital components.

Harneet Sangha (University of Leicester) presented an investigation into field-aligned current signatures, in particular Sub-Auroral Polarisation Streams (SAPS). The SAPS observations were attributed to the presence of substorm-injected plasma in the inner magnetosphere generating partial ring currents that divert along field lines into the ionosphere. Results from Lauren Orr (University of Warwick) demonstrated the large scale magnetic response of the system to substorms. Using more than 100 magnetometer stations from the SuperMAG array, Orr used a dynamical directed network to determine the characteristics of current systems. The results from Sangha and Orr provide insight to how energy propagates through the inner magnetosphere following substorm onset, through the development of large scale current systems mapping to the ionosphere.

Understanding how particles can access the inner magnetosphere can also be advanced through the use of global MHD models. Ravindra Desai (Imperial College London) used the Gorgon MHD model, combined with the Integrated Van Allen Radiation Belt (IVAR) model, to simulate the inner magnetosphere response to extreme space weather. An injection of highly energetic particles in the inner magnetosphere was observed. Desai showed that these particles can be injected to closed drift paths, contributing to the trapped populations.

In contrast, the highly distorted magnetosphere leads to losses for other particles on open drift paths, and the magnetopause distortion also results in the bifurcation of particle drift paths.

The meeting highlighted the significance of continued substorm activity, as opposed to a single isolated substorm event. Forsyth demonstrated that the effect of a single substorm on the radiation belts is highly variable, and determined that only 50% of substorms result in an increase in the radiation belt population. The response of the radiation belts to geomagnetic storms has also been found to exhibit a high degree of variability [e.g., Reeves, 1998]. However, work presented by Horne highlighted that it may be the duration of substorm activity that is crucial for driving radiation belt enhancements. Horne demonstrated that the occurrence of multiple substorm onsets provided the necessary sustained substorm injection activity that allows time for wave energisation (Figure 6). In terms of the ring current population, work presented by Jasmine Sandhu (MSSL, UCL) quantifies the substorm associated energisation of ring current ions [Sandhu et al., 2018b], and demonstrates that the characteristics of substorms associated with continued activity is also conducive to enhancing the inner magnetosphere compared to isolated events. Additionally, Yulia Bogdanova (Rutherford Appleton Laboratory) presented significant results on the storm/substorm relationship. Bogdanova assessed correlations in geomagnetic indices, and demonstrated a poor correlation between extreme storms and substorms, where the result suggests that the magnitude of substorms is not a key factor in shaping storm activity and that the relationship is more complex. The work presented in this meeting highlights that it the duration of substorm activity, as opposed to the strength or magnitude of the substorm, that could be the key factor in energising the inner magnetosphere.

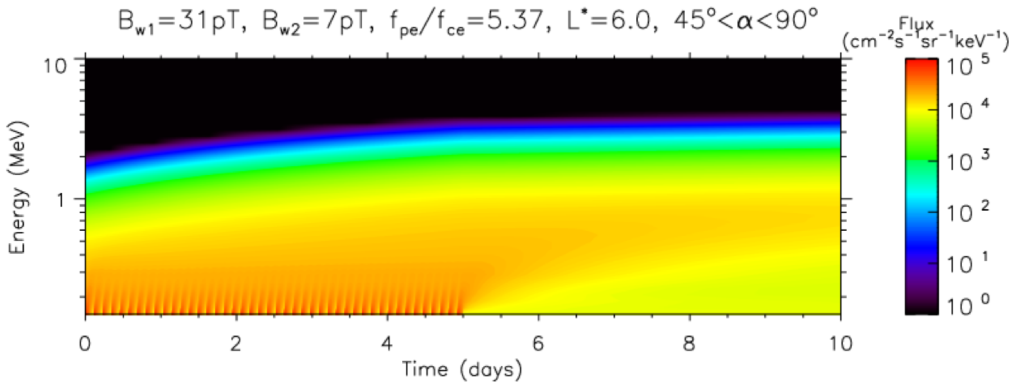

Figure 6: Modelled flux enhancements under a 5 day period of fast solar wind with substorm injections, followed by a 5 day period of low activity. The results show acceleration to high (> 2MeV) energies, which persist for days. (Horne)

The importance of the inner magnetosphere during storms

As well as considering the processes involved in generating geomagnetic storms, the meeting also included discussions on the implications of geomagnetic storms. This included considering how the radiation belts are energised and depleted during storms.

A key route of energy transfer in the inner magnetosphere is through the propagation of MHD waves, which can significantly energise the radiation belt population through wave particle interactions. Work by Jonathan Rae (MSSL, UCL) and Martin Archer (QMUL) explored the properties of Ultra Low Frequency (ULF) waves, which can couple to geomagnetic field lines and form large scale standing waves. The frequencies of these standing waves, termed the eigenfrequencies, and their spatial variations is a crucial factor in controlling how waves can propagate in the inner magnetosphere. Rae used ground magnetometer observations of wave power and eigenfrequencies to monitor storm time variations. A case study demonstrated that dramatic variations in the magnetic field configuration and the presence of heavy ions drove significant variations in the eigenfrequencies, and thus allowed for an increased accessibility of wave power to the inner magnetosphere. In contrast, Archer presented spacecraft observations of ULF waves using a novel sonification technique combined with a citizen science approach [Archer et al., 2018]. Similarly, changes in the inner magnetospheric plasma conditions, attributed to plasma refilling in the storm recovery phase, were observed to impart variations in the ULF wave properties (Figure 7). Our understanding of ULF wave properties are furthered by the probabilistic model of ULF wave power based on 15 years of data developed by Bentley. Bentley's model provides significant insight into the variability associated with this waves, and the importance of wave processes during geomagnetic storms.

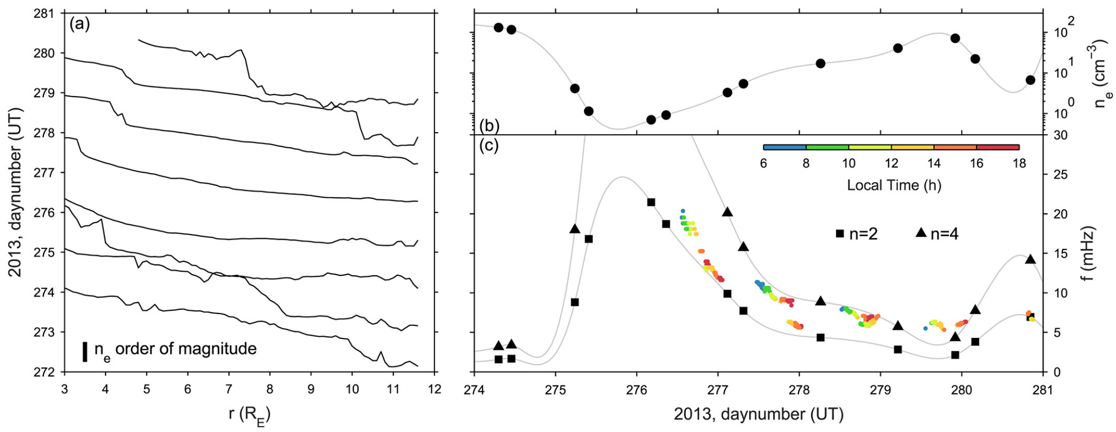

Figure 7: (a) Electron density profiles observed by THEMIS and (b) electron density at geosynchronous orbit. (c) The estimated eigenfrequencies based on density observations are shown in black and observed eigenfrequencies are shown by the coloured points, for both the 2nd (squares) and 4th (diamonds) harmonics. The observations are taken during the recovery phase of a geomagnetic storm are shown, and the results indicate that plasmaspheric refilling drives a decrease in eigenfrequencies. (Archer et al., 2018)

In terms of the radiation belts, the meeting hosted a broad consideration into how electron fluxes vary in response to a wide variety of storm-related processes. Storms are observed to exhibit dramatic variations in electron fluxes, including drop out events and energisations. Work by Hayley Allison (BAS/University of Cambridge) showed how, following a flux drop out event, a seed population in the inner magnetosphere can be effectively energised by chorus waves and redistributed by radial diffusion effects. The results demonstrate how these processes can act to rebuild the terrestrial radiation belts. Furthermore, the effects of radial diffusion were investigated by Rhys Thompson (University of Reading), providing valuable information into how diffusion can be characterised. Thompson suggests a probabilistic approach, as opposed to the used of commonly used deterministic models, this allowing for a clearer understanding of variability in diffusion rates.

The loss process of radiation belts during geomagnetic storms were also considered. John Ross (British Antarctic Survey) examined relativistic electron decay in the radiation belts due to plasmaspheric hiss and very low frequency transmitter waves. Frances Staples (MSSL, UCL) presented results based on spacecraft observations of magnetopause crossings, and identified that changes in the magnetopause position during the storm process is significant for radiation belt loss. Staples demonstrated that the magnetopause is located significantly closer to the Earth than shown in previous models, which has led to underestimations of magnetopause losses.

From an MHD modelling approach, Lars Mejnertsen (Imperial College London) applied a Gorgon MHD model to simulate the behaviour of the whole magnetosphere during a Carrington level storm. In addition, Mejnertsen examined the resulting ground induced currents, and explored how the response varies with different internal magnetic field conditions. The work highlights a consideration into long term changes in the internal geomagnetic field, and how this can impart variations in how the magnetosphere behaves during storm times.

Key outcomes and perspectives for the future

The discussion meeting raised several key questions in the community, as well as highlighting the broad array of excellent work being conducted. To conclude this review, we summarise the key outstanding questions:

- Can we account for the large degree of variability observed in the magnetospheric system?
- How should we define storms and substorms?
- Is continued substorm activity a key proponent in generating geomagnetic storms?
- What is the role of the inner magnetosphere, including the presence of heavy ions, in shaping storms and substorms?

Through formal and informal discussions, it is clear that no part of the system should be ignored when considering geomagnetic storms and substorms. These phenomena involve multiple aspects of solar wind-magnetosphere-ionosphere-thermospheric coupling, and there is no single dataset, or model, that can currently describe storms and substorms comprehensively. The Discussion Meeting highlighted the importance of regularly bringing the community together in order to share latest results and provide participants with a system-level overview.

The meeting also highlighted key avenues of progress in the field. The capabilities of MHD models, for example the Gorgon MHD model, suggest significant potential in exploring the large scale transfer of energy and reconfiguration of the system in response to solar wind driving and extreme events. Furthermore, the work presented demonstrated how the exploitation of high-quality data from long term missions such as Cluster, the Van Allen Probes, THEMIS, and AMPERE, and key ground-based remote sensing facilities such as SuperMAG and SuperDARN has allowed for significant advances in systematically exploring the magnetosphere. This is furthered by promising advances in data analysis techniques, including machine learning approaches. Unravelling these problems relies on a continuation of these approaches, fully exploiting available observational datasets, as well as looking forward to future opportunities. Of particular interest to this community is the ever-expanding SuperDARN network, which has in recent years allowed better observations during storms due to increasing mid-latitude observations, as well as the upcoming SMILE mission.

The Importance of Geomagnetic Indices (Box)

Storms and substorms are associated with significant changes in the magnetospheric plasma and magnetic field, as well as the enhanced flows of large scale electrical currents in the system. Ground magnetometers are therefore highly effective at measuring the global magnetic field perturbations due to the currents and we see consistent signatures in ground magnetometers during storms and substorms.

Since the late 1930s [Bartels et al., 1939, Rostoker, 1972], magnetic field data have been condensed into simple indices to indicate the level of geomagnetic activity. Specifically, there are the Dst index and the Sym-H index, which are derived from magnetometers that map to the ring current region and consequently experience significant North-South deviations during magnetic storms [e.g., Sugiura and Kamei, 1991]. A typical signature in the Dst or Sym-H index of a geomagnetic storm is shown in the Figure. Substorm activity can be encapsulated by the auroral electrojet indices (AE, AL, and AU) based on high latitude ground magnetometer data [Davis and Sugiura, 1966]. Characteristic “bays” in the AL index during a substorm is typically observed. On average, we see a clear signature in the indices for storms and substorms that agree well with the typical traces.

On this basis, storms and substorms are commonly identified from magnetic indices traces, and there exist a multitude of techniques that extract events from indices [e.g., Newell and Gjerloev, 2011, Turner et al., 2015, Forsyth et al., 2015, Murphy et al., 2018]. The wide variety of techniques exemplifies that it is not trivial to identify the events, and this is predominantly due to the large degree of variability within storms and substorms.

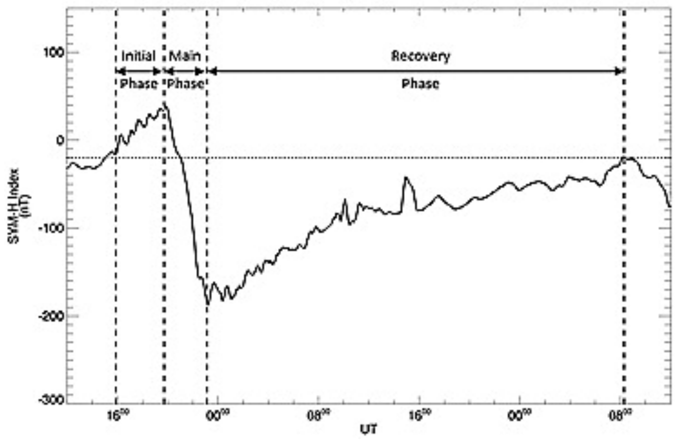

Figure: An example of the Sym-H trace for a typical storm. (Hutchinson et al., 2011)

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