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Developing the science of networks to quantify pattern in earth and space-based observations of space weather

Chapman, Sandra
UNIVERSITY OF WARWICK
UNIVERSITY HOUSE
THE UNIVERSITY OF WARWICK
COVENTRY, WEST MIDLANDS, CV4 8UW
GBR

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We are now in a ‘data rich’ era of space plasma physics observations which are unprecedented in their spatio-temporal coverage. The driver of space weather, the solar wind, is now monitored with time resolution from sub-second to decades, spanning multiple solar cycles. Historical data of geomagnetic activity at earth reaches back over 150 years. On earth, the data from 100+ ground-based magnetometers again spanning several decades is now readily available alongside multipoint satellite observations. This project brings new approaches to this wealth of data, harnessing the state of the art in trans-disciplinary approaches in time series analysis, statistical characterization, data analytics and the quantification of risk to provide quantitative insight on how the earth’s magnetosphere, a highly variable non-linear dynamical system, responds to the dynamical driving of the solar wind. Our results range from the first use of network science approaches to quantify the full spatio-temporal pattern of ground magnetic perturbations during space weather events, providing a benchmark for global space weather models, to quantifying the risk of extreme space weather events and how this risk varies with the solar cycle of activity.

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Developing the science of networks to quantify pattern in earth and space-based observations of space weather

S C Chapman

FA9550-17-1-0054 Final report [grant ending 30 September 2021 including no cost extension]

Abstract: We are now in a 'data rich' era of space plasma physics observations which are unprecedented in their spatio-temporal coverage. The driver of space weather, the solar wind, is now monitored with time resolution from sub-second to decades, spanning multiple solar cycles. Historical data of geomagnetic activity at earth reaches back over 150 years. On earth, the data from 100+ ground-based magnetometers again spanning several decades is now readily available alongside multipoint satellite observations. This project brings new approaches to this wealth of data, harnessing the state of the art in trans-disciplinary approaches in time series analysis, statistical characterization, data analytics and the quantification of risk to provide quantitative insight on how the earth's magnetosphere, a highly variable non-linear dynamical system, responds to the dynamical driving of the solar wind. Our results range from the first use of network science approaches to quantify the full spatio-temporal pattern of ground magnetic perturbations during space weather events, providing a benchmark for global space weather models, to quantifying the risk of extreme space weather events and how this risk varies with the solar cycle of activity.

Financials:

The project has supported a fraction of Chapman's time, travel, PhD students (50% matched funding, £33,417 per student from Warwick University) and desktop computing. PhD students Lauren Orr (2017 start), Aisling Bergin (2018 start) and Shahbaz Chaudhry (2019 start) are all funded on this grant. Lauren Orr successfully defended her thesis in 2020. We have been granted a no-cost extension to facilitate this spend profile. The most recent work with Orr and in collaboration with the British Geological Survey on space weather effects on the UK national HV grid was funded by an STFC Impact Acceleration Account, see:
https://stfc.ukri.org/files/stfc-impact-acceleration-account-booklet-2020/

New AFOSR grant FA8655-22-1-7056 builds on the research funded by this grant and will support 3 PhD students funded 50% by Warwick University and collaborative visits to NASA-JPL and JHU/APL.

Chapman was awarded one of only two of the 2017-18 Fulbright-Lloyd's of London Scholarships and this year-long programme with its focus on networks and statistical methodology in space weather was strongly complementary to the AFOSR project. For the bulk of the 2017-18 year (October-September), Chapman visited the Centre for Space Physics at Boston University also made a number of collaborative visits as detailed below. Chapman was granted sabbatical for spring term 2020 which supported an extended visit to NASA-JPL and a WOS visit to Kirtland AFB where she presented this work. Chapman was also supported for an extended visit in 2019 by the visiting researcher programme of the High Altitude Observatory (Boulder). Chapman is part of (invitation only) ISSI team 455 (Complex systems perspectives pertaining to the research of the near earth electromagnetic environment) supported by the International Space Science Institute (Bern). She was also recently appointed Adjunct Professor in Mathematics and Statistics, University of Tromso, Norway.

Covid impact: From March 2020 until now we have mostly been working from home and there has been no international travel. Space science datasets are generally available online so that all of our work could continue. Established collaborative projects have continued as normal, but new collaborative projects in the early stages of discussion have progressed more slowly, mainly due to the increased workload on our international collaborators. There have been further publications and numerous presentations at international conferences online, highlights include at the 2020 Fall AGU meeting where PhD student Orr gave an invited talk, and Chapman was awarded the Ed Lorenz Lecture. PhD student Bergin was awarded the 2021 MIST Rishbeth Prize for Best Student Talk. We are now back in office and are planning visits to JPL and JHU/APL in 2022.

Science:

Characterizing ionospheric current patterns and dynamics from ground based magnetometers using networks

L. Orr, S. C. Chapman, C. Beggan, Wavelet and network analysis of magnetic field variation and geomagnetically induced currents during large storms, Space Weather doi: 10.1029/2021SW002772 (2021)

L. Orr, S. C. Chapman, J. Gjerloev, W. Guo, Network Community Structure of Substorms using SuperMAG Magnetometers, Nature Communications, 12, 1842 doi:10.1038/s41467-021-22112-4 (2021)

L. Orr, S. C. Chapman, J. Gjerloev, Directed network of substorms using SuperMAG ground-based magnetometer data, Geophys. Res. Lett., doi:10.1029/2019GL082824 (2019)

J. Dods, S. C. Chapman, J. W. Gjerloev, Characterising the Ionospheric Current Pattern Response to Southward and Northward IMF Turnings with Dynamical SuperMAG Correlation Networks, J. Geophys. Res., 122, doi:10.1002/2016JA023686. (2017)

Key outcomes

- We have developed methodology to translate the vector time-series of 100+ ground based magnetometers into a dynamical directed network.
- The new methodology (in particular for calibrating for time varying offsets and different instrument sensitivities), is general and could be applied to other datasets (e.g. TEC).
- The network (and hence the full spatio-temporal pattern of correlation captured by the observations) can be described by a few time-dependent parameters- thus 100+ observations is reduced to a few meaningful time-varying parameters.
- We are able to use these network parameters to perform a statistical comparison across many events to quantitatively answers questions such as 'is there a typical, repeatable response of the ionospheric current system to a substorm?' and 'how does this compare with models for the ionospheric current system?' We have found that the substorm expansion phase is in almost all events characterized by a single, large-scale, highly correlated current system. This rules out the scenario that the current system is comprised solely of small structures/flow bursts, thus settling a major controversy but also throwing a spotlight on the models which can emphasize these flow bursts. However, we also found that the route to this highly organized current system is highly variable across events, which may explain the plethora of substorm current models that have arisen hitherto.
- Our work has introduced a new parameter- the network modularity- which is well known in network science but is completely new in space physics data. The modularity provides a quantitative measure of how structured and correlated the current system is and is a tool to

perform a statistical comparison across many events of the full topology of the current system.

- In collaboration with the British Geological Survey we have used the network analysis to quantify the risk of correlated Ground Induced Currents (GICs) to the UK national HV power grid. The network analysis has been reformulated to use Haar wavelet cross-correlation to isolate sharp changes in the magnetic field perturbations at earth which induce GICs in the HV grid.

Next steps: We will continue our longstanding collaboration with SuperMAG PI Jesper Gjerloev at JHU/APL to progress work on the SuperMAG network of ground based magnetometers which has been highly productive to date (Chapman, and AFOSR funded PhD student Orr visited JHU/APL in 2018). Our most recent Nature Communications benefited from a new collaboration with Weisi Guo (Cranfield) who is an internationally recognised expert on network science and we will continue this collaboration.
During an extended visit to Olga Verkhoglyadova and her team at NASA JPL (Chapman, and AFOSR funded PhD student Bergin visited in January 2020) we outlined a plan of work to apply the network methodology to TEC data. We are also beginning to apply network methodology to newly released 1sec resolution SuperMAG data which resolves Pc wave activity. New AFOSR grant FA8655-22-1-7056 will fund PhD students to work on the data and extended visits to JPL and APL by Chapman and her team.

The network modularity provides a tool for detailed quantitative comparison/data validation of space weather models and their predicted ground magnetic perturbations- it quantifies 'what aspects is the model getting right and when' and 'what aspects does the model need to get right?'

- Modularity, degree and other network parameters could be used to statistically quantify which aspects of the current system correlate with which features of the solar wind driving- may provide predictive capability.
- Designing space weather 'flags' – a few simple network parameters capture the relevant features of the detailed spatio-temporal pattern of magnetic perturbations on the ground.
- New projects include (i) quantifying the spatial pattern of correlation in PC waves and how this evolves in time, which directly relates to energetic particle enhancement of the ring current following substorms and storms, and is an indicator of the onset of storms (ii) constructing networks for TEC station data (rather than maps) and using network modularity to parameterize TEC enhancements.

Characterizing TEC enhancements

Key outcomes

We have made the first application of quantile-quantile (QQ) plots in space plasma data. This method provides a quantitative statistical comparison either between different datasets or between the same observed quantity at different times/under different conditions. Our preliminary study of TEC maps suggests several applications:

- We compared the distribution of TEC values during quiet and storm conditions. We are able to identify a clear signature of how extremes (high percentiles) of TEC are enhanced during storms even though the average may not change significantly. This has the potential to provide a measure with which to validate models- it is not sufficient for models to reproduce the average TEC, they need to reproduce the high percentiles.

- We found a solar cycle dependence in TEC storm enhancement at the high percentiles- may provide predictive capability.
- However we checked the above results against diurnal and seasonal variation and found persistent variability which is inherent in TEC maps due to a combination of uneven sampling, geographical variability and diurnal and seasonal effects.

Next steps: We will follow up on our collaboration with NASA JPL as above and also following on from a WOS visit to Kirtland AFB in Jan 2020 are discussing the following work:

- Reducing diurnal and seasonal variability- by localizing our statistical sample in UT.
- Quantifying which aspects of TEC variability correlate with which features of the solar and solar wind driving and magnetospheric state- may provide predictive capability.
- Using network parameterization (as above) to design TEC 'flags' – a few key time dependent parameters or indices that readily capture the spatio-temporal character of these information-rich TEC maps and how they vary in time.

<u>Solar cycle variability of 'space climate'</u>

A. Bergin, S. C. Chapman, N. W. Watkins, N. Moloney, Variation of geomagnetic index empirical distribution and burst statistics across successive solar cycles, JGR submitted (2021)

A. Bergin, S. C. Chapman, J. W. Gjerloev, AE, DST and their SuperMAG counterparts: The effect of improved spatial resolution in geomagnetic indices, J. Geophys. Res., doi:10.1029/2020JA027828 (2020)

S. C. Chapman, N. W. Watkins, E. Tindale, Reproducible aspects of the climate of space weather over the last five solar cycles, Space Weather, doi:10.1029/2018SW001884 (2018)

E. Tindale, S. C. Chapman, N. R. Moloney, and N.W. Watkins, The dependence of solar wind burst size on burst duration and its invariance across solar cycles 23 and 24, J. Geophys. Res. (2018) doi:10.1029/2018JA025740

E. Tindale, S. C. Chapman, Solar wind plasma parameter variability across solar cycles 23 and 24: from turbulence to extremes, J. Geophys. Res., 122. doi:10.1002/2017JA024412 (2017)

Key outcomes

- Coherent structures in the solar wind can drive space weather. They are seen in data as extended intervals, or 'bursts' of high values of a given parameter (magnetic energy density, Poynting flux and so forth). We found that the relationship between burst intensity and burst duration does not vary between active and more quiet solar cycles whilst the likely burst intensities do vary.
  - (i) This may have predictive capability since burst intensity determines burst duration and vice versa.
  - (ii) It provides a clear benchmark for models of solar wind propagation of structures such as CMEs.
- Over the last five solar cycles we found that whilst the overall amplitude of activity does vary with each distinct solar maximum, the larger excursions of quantities that characterize space weather follow an underlying distribution that does not change from one solar maximum to

the next. We can characterize this distribution with a Generalized Pareto Distribution functional form, each quantity has its own GPD parameters.

- To improve on these results one can in principle utilize the new set of geomagnetic indices that have recently been constructed from the 100+ ground based magnetometers in the SuperMAG network. These provide high resolution versions of the classic AE and DST indices which rely on 12, and 4, stations respectively. We looked into their properties in distribution across the last 5 solar cycles and found that the classic and new indices differ by an amount that is comparable to their natural solar cycle variation. We identified a method to renormalize DST onto its new counterpart but showed that this cannot be done for AE. These results are critical for future studies of space weather trends on solar cycle timescales.

Next steps

- Our results provide clear benchmarks for space weather models- do they give GPD distributions and do they have the observed GPD parameters?
- This may have predictive capability, a subset of the data at the beginning of a solar maximum interval may be enough to obtain the full distribution of large events, that is, how statistically likely they are, for the solar maximum interval as a whole.
- We found that F10.7, AE and DST all have this property and we will investigate how well these can be 'hindcasted'. These parameters are all highly relevant to space weather modelling.
- Crossing theory relates the underlying distribution of observations to the time spent above a threshold- this constrains the relationship between event average return period, duration, and the underlying distribution of observations. We already developed these ideas in earth climate timeseries (S. C. Chapman, N. W. Watkins, D. A. Stainforth, Warming trends in summer heatwaves, GRL, (2019) doi:10.1029/2018GL081004) and we have now shown how these constrain space weather event frequencies and durations within and across solar cycles. Given a prediction of the overall activity level of the next solar maximum, this constrains what the space weather event return period will be on average.

<u>Quantifying the risk of extreme space weather</u>

S. C. Chapman, S. W. McIntosh, R. J. Leamon, N. W. Watkins, The Sun's magnetic (Hale) cycle and 27 day recurrences in the aa geomagnetic index, Ap. J. (2021) doi: 10.3847/1538-4357/ac069e

McIntosh, S.W., Chapman, S., Leamon, R.J. et al. Overlapping Magnetic Activity Cycles and the Sunspot Number: Forecasting Sunspot Cycle 25 Amplitude. Sol Phys 295, 163 (2020). doi:10.1007/s11207-020-01723-y

S. C. Chapman, S. W. McIntosh, R. J. Leamon, N. W. Watkins, Quantifying the solar cycle modulation of extreme space weather, Geophys. Res. Lett. doi:10.1029/2020GL087795 (2020)

R. J. Leamon, S. W. McIntosh, S. C. Chapman, N. W. Watkins, Timing Terminators: Forecasting Sunspot Cycle 25 Onset, Solar Phys. 295:36 doi:10.1007/s11207-020-1595-3 (2020)

S. C. Chapman, R. Horne, N. W. Watkins, Using the aa index over the last 14 solar cycles to characterize extreme geomagnetic activity. Geophys. Res. Lett. (2020) doi:10.1029/2019GL086524

Key outcomes

There is a considerable body of work that attempts to quantify the occurrence likelihood of extreme space weather events by applying extreme value theory (EVT) to geomagnetic indices, particularly DST, for which there is data over the last 5 solar cycles. Given that these are by definition rare events, and the variable nature of the solar cycle, it is desirable to extend this type of analysis further back in time. The aa index is available over 14 solar cycles, however it is highly discretized as it is constructed from the K index (a number 0-9) at two antipodal stations. For this reason, standard EVT cannot be applied to the aa index as that would require resolving the peak values in any given event.

Our result has already attracted considerable interest and we were asked to provide figures from our analysis for a recent report to the US power industry: Magnetohydrodynamic (MHD) Modeling for the Further Understanding of Geoelectric Field Enhancements and Auroral Behavior during Geomagnetic Disturbance Events: EPRI, Palo Alto, CA: 2020. 3002017952

Chapman is also invited to speak at Risk Industry events due to the interest around this work: the Lloyd's of London Systemic Risk Masterclass Series 13 April 2021 *Recognising risk – the systemic effects of internet and utility outages,* and the PACICC Risk Officer's Forum Meeting on the topic, *Risks of Space Weather Phenomena*. Nov 17 2021 (PACICC is the resolution authority for Canada's P&C insurance industry).

- We showed that there is a good mapping between the annual averages of the top few percent of aa values and the annual DST minimum. This has allowed us to obtain the distribution of aa activity over the last 14 solar cycles and to translate this into the return times of years containing highly active space weather events categorized by DST level.
- The above results are a solar cycle average. We have been able to quantify the solar cycle variation of extreme events seen in the aa index by performing a Hilbert transform of daily sunspot number. This maps the irregular length solar cycle onto a regular 2 pi phase interval providing a solar cycle 'clock'. We identified a quiet phase of the cycle of about 4 years in duration and found that only a few percent of extreme events occurred during this quiet phase.
- Using the Hilbert transform to project forward in time, we are able in principle to make a prediction of the start time of the next solar cycle, although systematic uncertainties are challenging to quantify.
- We investigated the ~22 year Hale magnetic cycle using the Hilbert transform and a new analysis of the aa index. The R27 index (proposed by Sargent in 1985) tests for recurrences in the aa index and quantifies the occurrence of ordered states in the solar wind. We devised a new measure based on direct computation of the autocovariance of aa which is epoch-averaged over normalized Hale cycles using our Hilbert transform analysis. This new measure can achieve relatively high time resolution, so that we found that the transition between disordered solar wind around maximum, to ordered solar wind in the declining phase, is fast, occurring within a few solar rotations. This provides new insight into the Hale cycle variation of cosmic ray flux at earth, and the relative likelihood of occurrence of the most extreme space weather events (CME driven) and more moderate ones (corotating stream driven).
- We have found that the activity level of the available 6 solar cycles of F10.7 also under Hilbert transform conform to the same solar cycle 'clock' as the aa index. This again offers the possibility of predicting the onset and decay of F10.7 amplitude in real time.
- The length of each solar cycle orders the amplitude of the next cycle and our results of the Hilbert transform of daily sunspot number provide a sufficiently precise measure of each

solar cycle duration that we are able to quantify this relationship which can in turn support prediction of the amplitude of the next solar cycle.

Next steps: This work is a collaboration with Scott McIntosh (NCAR/HAO) and Bob Leamon (NASA Goddard) and Chapman was supported by a HAO visiting fellowship in September 2019.

- We will investigate (using hindcasting) to what accuracy the above results can be used to predict the 'switch off' and 'switch on' of extreme space weather activity in real time as the solar cycle progresses.
- Our new high-time resolution measure of the level of order/disorder in the solar wind is quite general and could be used in other parameters to gain a better understanding, and potential predictability, of changes in state and activity level through the solar cycle.

Wider complexity community: As well as visits to NASA-JPL, and JHU/APL highlighted above, this grant specifically supported Chapman to spend extended intervals at centers of excellence in complexity science, in particular the Santa Fe Institute. The SFI is invitation only and Chapman was granted a visit for the month of February 2018. AFOSR PhD student Lauren Orr, and STFC funded PhD student Liz Tindale, also visited SFI for one week during this period. All gave presentations and some new collaborations were initiated.

Chapman was also invited to the complex systems group at the University of Santiago, Chile in Jan 2018 (visit partially funded by U. Santiago). We have begun a new collaboration on entropy production and particle heating in turbulent plasmas.

International conferences: The work supported partially by this grant has garnered considerable international interest and Chapman has given invited presentations including at the key international conferences, the Fall AGU, EGU and AOGS.

<u>Invited talks at international conferences: S C Chapman</u>

Invited talk: Nonlinear wave and chaos workshop (NWCW17), San Diego, March 2017

Invited Paper: Workshop on Kappa Distributions at SigmaPhi2017 Corfu, July 2017, *Data quantile-quantile plots: model independent quantification of the evolution of the full distribution and application to solar wind turbulence and extremes,* <u>S. C. Chapman</u>, E. Tindale, N.W. Watkins, N. Maloney

Invited Keynote: SigmaPhi2017 Corfu, July 2017, Dynamical Networks characterization of space weather events

Invited talk: Lorentz Center workshop: 'Space Weather: A Multi-Disciplinary Approach', Leiden, September 2017

Invited Paper: Exploring Systems-Science Techniques for the Earth's Magnetosphere-Ionosphere-Thermosphere, Los Alamos July 2018

Invited Paper: 2018 Fall AGU meeting (SA23C) *Data analytics and 'deep time': Determining statistically reproducible properties of space climate over the last five solar cycles* <u>S. C. Chapman</u>, R. Horne, N. Watkins

Invited Paper: 2019 EGU meeting (NP2.2/EMRP2.5/ST2.7) *Solar wind driving and the dynamical magnetospheric response – data analytics approaches to observations across space and time*, <u>S. C. Chapman</u>, L. Orr, J. Gjerloev, N. Watkins

Invited Paper: 2019 AOGS meeting (ST01) *Data analytics approaches to STP: Statistical characterization of solar cycle variation in space climate, and dynamical networks approach to space weather*, S. C. Chapman, E. Tindale, L. Orr, J. Gjerloev, N. W. Watkins

Invited Paper: 2019 Fall AGU Meeting (NG22A) *Dynamical networks: a tool for identifying the evolution of spatio-temporal pattern in spatially irregular, multi (>100) point observations*, S. C. Chapman, J. Dods, L. Orr, J. W. Gjerloev, W. Guo

Invited Paper: SigmaPhi (Crete), July 2020

Invited Keynote: 10th International Conference on Complex Systems, Nashua NH July 2020

2020 Fall AGU Ed Lorenz Lecture

Contributed conference presentations: PhD students

Poster: EGU 2017 (Vienna), session ST2.4 (EGU2017-3347), *Solar cycle dependence of the distribution of solar wind in-situ plasma parameters, and how this drives solar wind-magnetosphere coupling parameters*, E. Tindale and S.C. Chapman

Poster and 1 minute lightening talk: Cambridge Networks Day (Cambridge), June 2017, *Dynamical Networks Characterization of Space Weather Events*, L. Orr, S. C. Chapman, J. W. Gjerloev, J. Dods

Poster: Autumn MIST 2017 (Burlington House, Piccadilly, London), November 2017, *Quantifying variability in fast and slow solar wind: From turbulence to extremes*, E. Tindale, S.C. Chapman, N. Moloney and N.W. Watkins

Talk: Autumn MIST 2017 (Burlington House, Piccadilly, London), November 2017, *Dynamical Networks Characterization of ground based magnetometer data*, L. Orr, S. C. Chapman, J. W. Gjerloev, J. Dods

Talk: Fall AGU 2017 (SH34A-02), *Quantifying variability in fast and slow solar wind: From turbulence to extremes*, E. Tindale, S.C. Chapman, N. Moloney and N.W. Watkins

Poster: Fall AGU 2017 (IN33B-0112), *Dynamical Networks Characterization of Space Weather Events* L. Orr, S. C. Chapman, J. Dods and J. W. Gjerloev

Talk: Spring MIST 2018 (University of Southampton), *Dynamical Networks approach to multipoint magnetometer data* L. Orr, S. C. Chapman, J. W. Gjerloev

Poster: System-Scale Data Analysis workshop 2018 (BAS, Cambridge), April 2018, *Dynamical Networks Characterization of substorms* L. Orr, S. C. Chapman, J. W. Gjerloev

Talk: Autumn MIST 2018 (Burlington House, Piccadilly, London), November 2018, *The Solar Cycle-Independent Scaling Properties of Solar Wind Bursts and the Implications for the Power Spectral Density and PDF*, E. Tindale, S.C. Chapman, N. Moloney and N.W. Watkins

Poster: Autumn MIST 2018 (Burlington House, Piccadilly, London), November 2018, *Information Flow in Directed Networks of Substorms*, L. Orr, S. C. Chapman, J. W. Gjerloev

Talk: RAS Specialist Discussion Meeting (Burlington House, Piccadilly, London), February 2019, *Directed networks of substorms from SuperMAG ground based magnetometer data*, L. Orr, S. C. Chapman, J. W. Gjerloev

Poster: RAS Specialist Discussion Meeting (Burlington House, Piccadilly, London), Feburary 2019, *Observational constraints on the distribution long-tail for F10.7 and geomagnetic indices over the last 5 solar maxima*, A. Bergin, S. C. Chapman, N. W. Watkins

Poster: Physics and Mathematics of Turbulent Flows at Different Scales Winter School, Les Houches, France, 2019, *Directed network of substorms from ground based magnetometer data*, L. Orr, S. C. Chapman, J. W. Gjerloev

Poster: Physics and Mathematics of Turbulent Flows at Different Scales Winter School, Les Houches, France, 2019, *Observational constraints on the distribution long-tail for F10.7 and geomagnetic indices over the last five solar maxima*, A. Bergin, S. C. Chapman, N. W. Watkins

Poster: EGU 2019 (NP1.2/CL4.16) *Directed networks of substorms from SuperMAG ground based magnetometer data*, L. Orr, S. C. Chapman, J. W. Gjerloev

Poster: EGU 2019 (ST4.1 EGU2019-7565) *A comparison of the substorm and storm-time observed values of the AE and DST geomagnetic indices to their SuperMAG counterparts over the last four solar cycles*, A. Bergin, S. C. Chapman, J. W. Gjerloev, N. W. Watkins

Talk: National Astronomy Meeting, Lancaster, 2019, *Directed network analysis of the substorm ionospheric current system and timings, using SuperMAG ground-based magnetometer data*, L. Orr, S. C. Chapman, J. W. Gjerloev

Talk: National Astronomy Meeting, Lancaster, 2019, *Large Excursions in AE and DST Geomagnetic Indices and their SuperMAG Counterparts: A Comparison Study*, A. Bergin, S. C. Chapman, J. W. Gjerloev

Talk: European Space Weather Week, Liege, 2019, *How increasing the number of ground magnetometer stations affects geomagnetic indices: Comparing AE, DST and their SuperMAG counterparts*, A. Bergin, S. C. Chapman, J. W. Gjerloev

Poster: European Space Weather Week, Liege, 2019*, Using dynamical networks to characterize and quantify the evolving spatio-temporal ground pattern of magnetic disturbance seen by 100+ ground based magnetometers with SuperMAG*, L. Orr, S. C. Chapman, J. Gjerloev

Poster: Fall AGU 2019 (SM31E-3193) *AE, DST and their SuperMAG Counterparts: The Effect of Improved Spatial Resolution in Geomagnetic Indices*, A. Bergin, S. C. Chapman, J. W. Gjerloev

Poster: Autumn MIST 2019 (Postponed), (Burlington House, Piccadilly, London), January 2020, *Using dynamical networks to characterize and quantify the evolving spatio-temporal ground pattern of magnetic disturbance seen by 100+ ground based magnetometers with SuperMAG*, L. Orr, S. C. Chapman, J. W. Gjerloev, W. Guo

Poster: Autumn MIST 2019 (Postponed), (Burlington House, Piccadilly, London), January 2020*, Effect of Improved Spatial Resolution in Geomagnetic Indices: AE, DST and their SuperMAG Counterparts*, A. Bergin, S. C. Chapman, J. W. Gjerloev

Talk: PrExDA 2020: Predicting Extremes by Data-Driven Analytics (Session A: Perspectives on Predicting Extremes), October 2020, *Directed network modelling of geomagnetic activity*, L. Orr, S. C. Chapman, J. W. Gjerloev, W.Guo, C. D. Beggan

Invited Talk: Fall AGU 2020 (SM015): Data-Based Modeling and Uncertainty Quantification for Space Weather I), December 2020, *Network-based quantification of the Substorm Current Wedge*, L. Orr, S. C. Chapman, J. W. Gjerloev, W.Guo

Poster: Autumn MIST 2020 (Virtual), Session 2, *Quantifying the statistical variation of return period, amplitude and duration of bursts in the AE index across successive solar cycles*, A. Bergin, S. C. Chapman, N. R. Moloney and N. W. Watkins

Poster: AGU 2020 (Virtual), session SM004-0010, *Statistical quantification of the variation in return period, amplitude and duration of space within and between successive solar cycles*, A. Bergin, S. C. Chapman, N. R. Moloney and N. W. Watkins

Talk: Autumn MIST 2020 (Virtual)*, Wavelet and network analysis of magnetic field variation and geomagnetically induced currents during large storms*, L. Orr, S.C. Chapman, C. D. Beggan

Poster: Autumn MIST 2020 (Virtual), Session 3, *Space-weather events characterized using dynamical network analysis of ground based magnetometers*, S.Chaudhry, S. C. Chapman, and J. W. Gjerloev

Poster: AGU 2020 (Virtual), session SM006-0016, *Quantifying space-weather events using dynamical network analysis of ground based magnetometers*, S.Chaudhry, S. C. Chapman, and J. W. Gjerloev

Talk: EGU 2021 (Virtual) (NP4.2 EGU21-4641) *Quantifying variation of geomagnetic index empirical distribution and burst statistics across successive solar cycles*, A. Bergin, S. C. Chapman, N. Moloney, N. W. Watkins

Poster: EGU 2021 (Virtual) (NP4.2 EGU21-5804) *Quantifying space-weather events using dynamical network analysis of ground based magnetometers*, S. Chaudhry, S. C. Chapman, J. Gjerloev

Talk: NAM 2021 (Virtual) *Solar cycle variation in empirical distribution and burst statistics of auroral electrojet and ring current geomagnetic indices*. A. Bergin, S. C. Chapman, N. R. Moloney, N. W. Watkins [awarded the Risbeth Prize]

Autumn MIST 2021 (Virtual) *Dynamical network characterization of the spatially coherent Pc wave response to geomagnetic storms as seen by SuperMAG*, S. Chaudhry, S. C. Chapman, and J. W. Gjerloev

Selected contributed presentations at international conferences: Chapman

Talk: Fall AGU 2017 (SM14A-08) *Dynamical Networks Characterization of Geomagnetic Substorms and Transient Response to the Solar Wind State*, J. Dods, S. C. Chapman and J. W. Gjerloev

Poster: Fall AGU 2018 (SH43B-3696) *Testing for the direct propagation of scaling fluctuations from the outer corona to the solar wind* B. Hnat, S. C. Chapman, N. W. Watkins

Poster: Fall AGU 2018 (SA23C-3198) *Using dynamical networks to characterize the full spatio-temporal dynamics and information propagation across 100+ SuperMAG ground based magnetometers*, S. C. Chapman, L. Orr, J. W. Gjerloev

Talk: Variability Workshop Washington DC 2018 *Quantifying Intermediate Time Scale Variability in TEC*, S. C. Chapman

Poster: EGU 2019 (ST4.1 EGU2019-4086) *Observational constraints on the climate of space weather and implications for the upcoming solar maximum*, E Tindale, S. C. Chapman, N. W. Watkins, R. Horne

Poster: AOGS 2019 (ST31-A004) *Dynamical Network Quantification of the Spatio-temporal Pattern of Substorm Ground Magnetic Perturbations Using SuperMAG*, S.C. Chapman, L. Orr, J.W. Gjerloev

Talk, at European Space Weather Week, Liege, 2019 *Statistical quantification of extreme space weather events across multiple solar cycles: the Carrington event in context*, S. C. Chapman, R. B. Horne, N. W. Watkins

Talk: in ULTIMA Forum on Ground-based Magnetometers at mini-GEM Workshop, San Francisco 2019, *Dynamical networks: a tool for identifying the evolution of spatio-temporal pattern in spatially irregular, multi (>100) point observations*, S. C. Chapman, J. Dods, L. Orr, J. W. Gjerloev, W. Guo

Talk: Fall AGU 2019 (GC44C-08) *Warming trends in summer heatwaves and extended warm spells in winter seen in the Central England Temperature time series*, S. C. Chapman, D A Stainforth, E J Murphy and N W Watkins

Talk: Fall AGU 2019 (SM33A-07) *Quantifying the statistical distribution of extreme space climate and its variability within and across multiple solar cycles*, S. C. Chapman, N. W. Watkins, R. B Horne, E. Tindale, S. W. McIntosh, R. J. Leamon

Talk: EGU 2021 (ST1.1 EGU21-2555) *A clock for the Sun's magnetic Hale cycle and 27 day recurrences in the aa geomagnetic index* S. C. Chapman, S. McIntosh, R. Leamon, and N. W. Watkins

International seminars (Chapman):

Plasma Physics Group, Columbia University, October 2017
Center for Space Physics, Boston University, November 2017
JHU/APL Laurel, MD November 2017
University of Santiago Chile January 2018
NASA-JPL Pasadena January 2018
General Atomics DIII-D lab January 2018
Santa Fe Institute, NM 7 February 2018
HAO Boulder September 2019
NASA-JPL Pasadena January 2020
Kirtland AFB (WOS visit) February 2020
DIAS, Dublin 12 October 2021