Advances in Techniques in Space Plasma Physics

10th May 2024 at RAS Burlington House

Shannon Killey (Northumbria University), Sarah Bentley (Northumbria University), Alexandra Fogg (Dublin Institute for Advanced Studies, she/her), Matthew Lang (British Antarctic Survey), Rachel Black (British Antarctic Survey, University of Exeter)

Doors Open / Tea and Coffee		10:00 - 10:30
Understanding Observations		10:30 – 11:50
10:30 – 10:50	Connor O'Brien	PRIME-SH: A Data-Driven Probabilistic Model of Earth's Magnetosheath ***(invited)***
10:50 – 11:05	Christopher J. Owen	High-time resolution observations of 2D and 3D electron velocity distribution functions captured by Solar Orbiter SWA
11:05 – 11:20	Alan Wood	The Mid-Latitude Ionosphere Observed with the International LOFAR Telescope
11:20 – 11:35	Jacob Parrott	New Measurement Technique for the Martian Ionosphere: First Results of Mars Express - ExoMars Trace Gas Orbiter Mutual Radio Occultation
11:35 – 11:50	Dale Weigt	A novel technique to predict magnetic flux emergence on the Sun
Break		**11:50 – 11:55**
Improving Modelling Capabilities		11:55 – 13:00
11:55 – 12:15	Jonas Suni	Vlasiator: Recent improvements, discoveries, and techniques using global magnetospheric hybrid-Vlasov modelling ***(invited)***
12:15 – 12:30	Daniel Ratliff	Wave Action Models for Whistler-Mode Chorus: A Theoretical Approach to Understanding Large Amplitude Chorus Activity
12:30 – 12:45	Georgios Nicolaou	Forward models of space plasma instruments for the accurate determination of plasma bulk parameters
12:45 – 13:00	Harley Kelly	Dynamic Mode Decomposition for efficiently extracting waves in big data: Application to Kelvin-Helmholtz waves in a global MHD simulation
Lunch		**13:00 – 14:00**

Combined Approaches		14:00 – 15:10
14:00 – 14:20	Sanita Vetra-Carvalho	TBC ***(invited)***
14:20 – 14:35	Andy Smith	Automatic Encoding of Unlabeled Two Dimensional Data Enabling Similarity Searches
14:35 – 14:50	Cara Waters	Coupling Simulation and Spacecraft Data Using Clustering and Neural Networks: Applications to Magnetic Reconnection
14:50 – 15:05	Kendra Gilmore	Magnetospheric time history: How much do we need for forecasting?
15:05 – 15:10	Clare Watt	RASTI advertisement
Posters		15:10 – 15:35
Refreshments, RAS AGM		15:35 onwards

Abstracts

Understanding Observations		
Connor O'Brien Walsh, B; Zou, Y; Qudsi, R; Tasnim, S; Zhang, H; Sibeck, D.	PRIME-SH: A Data-Driven Probabilistic Model of Earth's Magnetosheath ***(invited)***	As the solar wind encounters Earth's magnetosphere and diverts around it, a shock is formed that heats and compresses the plasma and warps the magnetic field frozen into it. This shocked plasma and magnetic field, known as the magnetosheath, is what drives energy transfer at the magnetopause. Due to orbital constraints there is no continuous in-situ monitor of magnetosheath conditions. Studies of solar wind magnetosphere interaction typically rely on solar wind conditions measured at L1 propagated to Earth by some algorithm, which are then either used directly or used to drive some model of the magnetosheath. This process has numerous points of uncertainty, from the choice of propagation algorithm to the choice of magnetosheath model (or lack thereof). To address these concerns with the traditional approach, this study develops a data-driven model of the magnetosheath that uses data from L1 as its input. This new model, called PRIME-SH, adapts a Bayesian recurrent neural network architecture that is capable of estimating uncertainties for its predictions. This new model is verified to be accurate in a statistical sense, and is also capable of representing physics that is not explicitly incorporated in the model during training.
Christopher J. Owen Razavi, A.; Nicolaou, G.; Maksimovic, M.; Horbury, T.; Louarn, P.; Anekallu, C.; Berard, D.; Bonnin, X.; Darwish, K.; Fortunato, V.; Kataria, D.; Lewis, G.; Mele, G.; Watson, G.	High-time resolution observations of 2D and 3D electron velocity distribution functions captured by Solar Orbiter SWA	For the Solar Wind Analyser Electron Analyser System (SWA/EAS) on Solar Orbiter, telemetry constraints limit normal mode data return to a maximum of 1 3D electron velocity distribution function (eVDF) every 10 seconds. To address this, two novel methods for capturing brief periods of high time resolution data are used to enable analysis of phenomena such as shocks and wave-particle interactions. Firstly, SWA has a rolling buffer capable of storing 1-second resolution 3D eVDF data for 5 minutes. To capture events rolling through this buffer, B-field data from MAG and solar wind ion density and velocity from SWA/PAS are transmitted to the RPW instrument with a few seconds latency. An RPW algorithm uses these data to detect any shock passage during the previous few minutes. A positive result sent to SWA triggers a buffer freeze and adds resulting data to the telemetry stream. Secondly, the EAS burst mode data taking is guided by the B-field communicated from MAG. EAS records only 2 slices of the eVDF which contain the field- and anti-field-aligned directions, from which we derive a 2D pitch angle distribution with 0.125 sec cadence. In this presentation we summarize these novel methods and illustrate examples of their use.

Alan Wood Dorrian, G.D.; Boyde, B.; Trigg, H.; Fallows, R.A.; Mevius, M.	The Mid-Latitude Ionosphere Observed with the International LOFAR Telescope	The Low Frequency Array (LOFAR) is one of the most advanced radio telescopes in the world. When radio waves from a distant astronomical source traverse the ionosphere, structures in this plasma affect the signal. The high temporal resolution available (~10 ms), the range of frequencies observed (10-90 MHz & 110-250 MHz) and the large number of receiving stations (52 across Europe) mean that LOFAR can also observe the effects of the midlatitude and sub-auroral ionosphere at an unprecedented level of detail. The University of Birmingham are leading a four-year research programme which seeks to determine the morphology, origin and evolution of plasma structures inferred from observations made using LOFAR, and to establish the implications of these observations for Earth system science. Multiple observational case studies have been undertaken. These show substructure within a sporadic-E layer, substructure within a Medium Scale Travelling Ionospheric Disturbance (TID), a Small Scale TID and symmetric quasi-periodic scintillations amongst others. The small-scale sizes of many of these features implies a local source, either due to instability processes in the mid-latitude ionosphere or due to drivers from below. Work to determine instability growth rates using LOFAR is discussed, alongside multi-instrument studies to investigate driving from below.
Jacob Parrott Svedhem, H.; Witasse, O.; Wilson, C.; Müller-Wodarg, I.	New Measurement Technique for the Martian Ionosphere: First Results of Mars Express - ExoMars Trace Gas Orbiter Mutual Radio Occultation	Spacecraft-to-spacecraft radio occultations experiments are being conducted at Mars between Mars Express (MEX) and Trace Gas Orbiter (TGO), the first ever extensive inter-spacecraft occultations at a planet other than Earth. Due to the UHF frequency, this measurement technique is adept at sensing ionospheres and this unique spacecraft configuration allows for measurements around noon and into the deep-night. This presentation shall show the first 102 such occultations. Of these, 63 observations have to-date resulted in the extraction of vertical electron density profiles. These observations are the successful results of a major feasibility study conducted by the European Space Agency to use pre-existing relay communication equipment for radio science purposes.
Dale Weigt Korpi-Lagg, A.; Korpi-Lagg, M.	A novel technique to predict magnetic flux emergence on the Sun	Helioseismology allows us to probe the turbulent and dynamic solar interior, utilising Doppler velocity measurements to determine the properties of pressure waves (p-modes) and surface gravity waves (f-modes). The potential of the f-modes to predict magnetic flux emergence has only very recently been recognised with recent reports of the f-mode to be enhanced 1-2 days prior to the appearance of concentrated magnetic fields which in turn form active regions. The f-mode was then observed to be continuously quenched once the flux was fully emerged. However the technique relied on various normalisations that introduce bias to the f-mode computation

		(e.g., using a selected 'quiet' patch). Here, we eliminate such biases using a data-driven flat-fielding technique at the selected location. This is more sensitive to fluctuations and obtains the f-mode power at any location on the solar disk and is independent of any normalisation from 'quiet' regions, making it more robust and accurate than current techniques. Here, we demonstrate that our novel technique reproduces f-mode behaviour observed from previous studies, with the addition of error bars and additional science information (e.g., geometry). The novel technique may be a useful proxy for predicting solar flux emergence, potentially improving space weather forecasting.
Improving Modelling Capabilities		
Jonas Suni	Vlasiator: Recent improvements, discoveries, and techniques using global magnetospheric hybrid-Vlasov modelling ***(invited)***	Modelling the near-Earth space plasma environment accurately is a difficult task. Simulations using fluid approximations can be run on small HPC systems and even regular computers, but including kinetic effects greatly increases the computational costs. Global kinetic simulations of near-Earth space are necessary, however, for understanding many important space plasma phenomena and their potential effects on space weather. Vlasiator is a highly parallelised HPC global magnetospheric hybrid-Vlasov model that can model ion kinetic phenomena in the entirety of near-Earth space. Vlasiator has been used to study foreshock waves, magnetosheath jets, particle precipitation, magnetotail eruptions, magnetic topology, etc. In this presentation, we discuss the need for global kinetic simulations and the computational costs associated with them, describe the Vlasiator model, and highlight a few of the studies achieved with the model.
Daniel Ratliff Allanson, O.; Stawarz, J.; Watt, C.; Rasinskaite, D.; Chakraborty, S	Wave Action Models for Whistler-Mode Chorus: A Theoretical Approach to Understanding Large Amplitude Chorus Activity	Whistler-Mode Chorus (WMC) waves are an important contributor to space weather as intense, large amplitude WMC activity has the potential to energise particles to hazardous levels. This has motivated several studies into their statistics to determine when and where large amplitude activity is expected and inform how wave activity is implemented in radiation belt modelling. Conventionally believed to be largely Gaussian in nature, WMC data shows active wave regions have significantly non-Gaussian statistics in tandem with large amplitude chorus activity – so what drives this change in statistical nature and how might we model it? In this talk, we present a theoretical framework to produce and explore WMC wave statistics via a wave action model. This first-generation of the model describes the energy transfer between parallel-propagating WMC waves in the magnetosphere via 4-wave interactions facilitated by wave-particle interactions. This approach not only generate frequency and amplitude distributions representative of the

		non-Gaussian statistical observations but links these statistical changes to a key nondimensional index. This index, like that used by NOAA and ECMWF to characterise extreme ocean dynamics, provides a simple “yardstick” in identifying regions of increased (and possibly dangerous) wave activity in WMC wave regions.
Georgios Nicolaou Ioannou, C.; Owen, C. J.	Forward models of space plasma instruments for the accurate determination of plasma bulk parameters	Forward models are used to simulate observations of plasma instruments in specific plasma environments. Typical data analyses use forward modeling to optimize the plasma bulk parameters that fit the actual observations. However, several studies use simplified instrument models in order to reduce the computational time required for the analysis. Here, we develop a high-resolution forward model of a typical electrostatic analyser incorporating aperture deflectors and a position sensitive detector. We simulate measurements of this concept instrument in typical solar wind plasma protons, without any simplification in our calculations. We then analyse the simulated measurements with the standard simplifications implemented in the analysis and determine the plasma bulk parameters. We then compare the determined bulk parameters to those we use to simulate the observations in the first place. This comparison shows that the standard simplifications of the analysis can lead to significant misestimations of the plasma properties. Moreover, we show that the misestimations get larger when the analysis is performed in colder and/or faster plasmas. Finally, we demonstrate the application of the forward modeling techniques to the analysis of observations by Solar Orbiter. This study provides a guide to optimize forward models of similar instruments obtaining measurements in several plasma regimes.
Harley Kelly Archer, M.; Eastwood, J.; Desai, R.; Eggington, J.; Heyns, M.; LaMoury, A.; Mejnertsen, L.; Chittenden, J.	Dynamic Mode Decomposition for efficiently extracting waves in big data: Application to Kelvin-Helmholtz waves in a global MHD simulation	In space plasma physics, waves are typically identified using Fourier methods. However, these do not reduce the quantity of data, making comprehensive analysis challenging even across a single global simulation run. Dynamic mode decomposition (DMD) is a data-driven data reduction technique originally developed for hydrodynamics. It decomposes a non-linear system into a small set of modes, each which can be fully reconstructed as the product of a spatial pattern and its time evolution at fixed frequency and growth rate. This makes DMD superior to other dimensionality reduction methods (such as principal component analysis) when applied to oscillatory spatiotemporal data, since DMD modes have clearer physical meaning. In hydrodynamic applications DMD is applied to velocity perturbations, however, in space plasmas the magnetic field must also be incorporated in a physically comparable way. Recognising that dimensionality reduction techniques try to maximise the explainable variance, we rescale velocity, pressure, and magnetic field perturbations so their variances correspond to wave energy densities. We show an application of DMD to a Gorgon global MHD simulation of magnetopause Kelvin-Helmholtz waves and rolled-up vortices.

		This has revealed that at each local time there exists a superposition of KH-modes present, corresponding to both locally generated and advected waves.

Combined Approaches

Sanita Vetra-Carvalho	TBC ***(invited)***	TBC
Andy Smith Rae, I. J.; Stawarz, J. E.; Sun, W.; Bentley, S.; Koul, A.	Automatic Encoding of Unlabeled Two Dimensional Data Enabling Similarity Searches	We often have large, unlabelled datasets in space physics, where the phenomenon of interest only appears rarely. Understanding the underlying physics of the system from rare observations is a challenge, and locating complementary, similar observations in large datasets can be prohibitively time consuming. We present an automated, self-supervised method by which the key information from two dimensional data can be encoded into a vector representation. This representation (encoding/embedding) contains the key information describing the data; we can then use the distance between vectors to assess the similarity of the observations. We test the potential of this method with two example datasets (~ five thousand images) – spacecraft in situ electron velocity distributions and auroral all sky images. In the case of the electron distributions, we test a “seed” image of a rare phenomena – corresponding to the region of space near the site of magnetic reconnection. We then extract the six closest partners of this image, using the distance between the embedding vectors. The two closest neighbours of the seed image represent two “new” observations close to the site of magnetic reconnection.
Cara Waters Eastwood, J. P.; Fargette, N.; Goldman, M.; Newman, D.; Lapenta, G.	Coupling Simulation and Spacecraft Data Using Clustering and Neural Networks: Applications to Magnetic Reconnection	In space plasma physics, determining the relative position between spacecraft and the phenomena they observe carries a degree of uncertainty. Typically, the position is determined by using techniques based on assumptions unique to each event studied. In an attempt to generalise this, we use a recurrent neural network (RNN) in combination with clustering techniques on a 2.5D particle-in-cell simulation of symmetric reconnection, thus providing structural context to magnetotail reconnection. k-means clustering is a method that aims to partition data such that alike data values in similar regions of parameter space share a label. For spacecraft data, this parameter space can incorporate any number of observed plasma and field measurements. Initially, we cluster the simulation to find six physically meaningful regions which correspond to pairs of inflows, outflows, and separatrices. Next, we train an RNN on random walks through the clustered simulation data emulating spacecraft trajectories. Finally, the RNN can be applied to in-situ data to provide the previously

		lacking structural context. The computational efficiency of this method allows us to apply the same RNN to various magnetotail reconnection events for statistical studies. Due to the versatility of the outlined methods, this process is not limited to reconnection studies.
Kendra Gilmore Bentley, S. N.; Smith, A. W.	Magnetospheric time history: How much do we need for forecasting?	The Earth's magnetic field varies on scales of giga years to milliseconds related to internal, external, and anthropogenic sources. It is essential to know what the intrinsic periodicities of the magnetic field are in order for us to process data correctly, model and predict the magnetospheric processes accurately. Using Short Term Fourier Transform (STFT), we investigate the periodicities of the different magnetic field components across different locations. Extending this to machine learning, many methods neglect the temporal aspect of the data instead reducing it down to averages. However, the state-of-the-art time series machine learning algorithm, Long Short Term (LSTM)-RNN, is adapted to sequential data types like time series by considering a set amount of history. As ML models have the inherent problem of being a black box, we want to understand the capabilities of LSTMs. By studying synthetic periodic data with LSTMs and comparing the results using STFT to the true signal, we can assess how well the ML model captures the physics of the system and what the limits of this method are.
Clare Watt	RASTI advertisement	
Posters		
Martin Archer	Applying data-driven density estimation to improve magnetospheric imaging	Imaging the dynamic solar-terrestrial interaction from space is an emerging direction in space plasma physics, which can clearly complement in situ spacecraft and ground-based measurements. However, expected count rates of Soft X-rays or Energetic Neutral Atoms from the magnetosphere are typically low, thus signal-to-noise levels become crucial. It is becoming clear that simple spatiotemporal binning of event counts may struggle to resolve typical scales of magnetopause dynamics, e.g. for the upcoming SMILE mission. On the other hand, data-driven density estimation techniques from the field of statistics may help in this regard. Instead of pixels with sharp edges at fixed locations, density estimation sums over smooth functions (kernels) centred on each observation's location. This technique has convergence and continuity benefits over binning, and several methods on how best to scale the width of these kernels based on the data already exist. I present preliminary applications to simulated SMILE SXI data. These show clear improvements over standard techniques as well as enabling a quantification of what scales can be resolved. Further advancements which could be subsequently applied are also discussed.

Sam Boardman Allanson, O.; Osmane, A.; Elvidge, S.	Extending Quasilinear Theory for Particles Near 90 Degrees	Energetic electron populations that are present in the Earth's outer radiation belt are an outstanding natural environment allowing us to discover the nature of how the dynamics of relativistic charged particles evolve, how they are lost, and how they are accelerated. These radiation belt electrons are trapped when pitch angles are outside the loss cone. Losses and acceleration are often well accounted for when considering wave-particle interactions where particles have pitch angles in intermediate ranges. However, current models rely on a quasilinear theory that does not always explain the observable loss rates of particles with pitch angles near 90 degrees. One possible solution to this 90-degree problem is resonance broadening, wherein wave-particle interactions can occur at a range of wavelengths near to the resonant value rather than only for perfect resonance. Here we will highlight a derivation of diffusion coefficients under the weak turbulence approximation before suggesting and analysing links with a potential nonlinear extension to quasilinear theory. We provide preliminary fits comparing quasilinear results with test particle simulations. These simulations track the evolution of electron energy and pitch angles following resonant interactions with parallel-propagating whistler-mode chorus waves within a uniform background magnetic field.
Shannon Killey Rae, I. J.; Smith, A. W.; Watt, C. E. J.; Bentley, S. N.; Chakraborty S.; Sandhu, J. K.	Mapping Evolution of Relativistic Electron Distributions During Geomagnetic Storms	The behaviour of relativistic electrons in the Van Allen Radiation Belts is contingent on a wide range of physical processes that drive acceleration, loss or transport within the magnetosphere across different energies and pitch angles. Each individual process can be linked to a specific energy-dependent pitch angle distribution (PAD). However, these competing processes can often operate simultaneously, which make electron behaviour difficult to diagnose and forecast. We employ machine learning techniques to classify the shapes of 7 years of Van Allen Probe Relativistic Electron Proton Telescope (REPT) PADs. We find that there are 6 specific PAD shapes, two each of: pancake, butterfly, and flattop, corresponding to wave-particle interactions and radial diffusive processes across the inner magnetosphere. We further show the evolution of storm-time PADs through the analysis of 45 geomagnetic storms from 2012-2018. We find that the majority of PADs are driven via a combination of radial diffusion and wave-particle interaction processes i.e., flattop and pancake. Butterfly distributions, on the other hand, can be separated into those driven via magnetopause shadowing and those via wave-particle interaction, demonstrating that PAD

		characterisation is a key component of understanding Van Allen Radiation Belt dynamics.
Anna Parsec-Wallis Coates, A.; Nicolaou, G.	Instrument design proposition for optimal high energy resolution of negative ions	Following the success of Cassini-Huygens mission and astonishing discoveries (Coates et al., 2007, 2009, 2010) made during the time of its operation, the data produced still holds a myriad of unsolved mysteries. Ahead of the recently announced large-class ESA science mission with priority mission targets being Enceladus and Titan (ESA, 2024), it is paramount to measure and analyse data with the most advanced methods available to unravel details that were held from the scientific community up until now. In this poster we will present the Cassini electron spectrometer (CAPS-ELS) with the details of outstanding questions posed by the received data. The primary focus of our research is to resolve the composition of icy moon atmospheres and understand the prebiotic chemistry involved. Detection of negative ions and their analysis is essential to our research. Studying and analysing negative ions is helping us to understand the prebiotic environment and hence how complex organic molecules are produced in an early Earth-like atmosphere. Negative ions were detected by CAPS-ELS which was an electron-oriented instrument. We will set the necessary technical requirements for an instrument capable of detecting negative ions and analysing their charge, energy and mass and present its initial design.
Sarah N. Bentley Stout, J; Thompson R; Ratliff D J; Watt C E J.	Radiation belt modelling: new metrics and what they indicate we should focus on.	Radial diffusion is a process in Earth's radiation belts that determines the large-scale, gradual movement of electrons towards and away from the Earth. We present a series of idealised radial diffusion experiments designed to inform us how to analyse ensemble models, which are need to characterise the complex dynamics of the radiation belts for space weather forecasting. We present two metrics. Time to monotonicity indicates how long a localised enhancement takes to diffuse away, while mass and energy moments allow us to quantify the evolution of the system in terms of inner and outer boundaries and loss. These metrics are successful because the consider the whole domain, and radial diffusion is dependent on location. We find that gradients in the particle phase space density distribution affect the system evolution more than the diffusion coefficients. We also find that the length of the simulation domain changes the way the system evolves. These raise questions about our next steps in radiation belt modelling.

Rachel Black

Allanson, O; Meredith, N.P; Hillier, A.

Investigating the variability of chorus waves in the radiation belts for improved understanding of nonlinear interactions

Earth’s radiation belts can be described by two zones containing energetic charged particles; a more stable inner belt, and a highly dynamic outer belt. The electron dynamics within the outer belt occur over many different time and length scales, governed by several processes including wave-particle interactions. This variability means that it is difficult to create a model capable of real-time prediction.

The most common method used by the international community for reproducing radiation belt dynamics involves Fokker-Planck diffusion models. Whilst, in many cases, these models effectively describe the global changes and interactions within the region, the Fokker-Planck approach depends upon a quasilinear theory. This assumes "small" amplitude and incoherent waves; however, recent spacecraft observations have shown that this assumption may not always hold. Accounting for this type of wave would require an extension of the modelling to include nonlinear effects.

In this work, we utilise two datasets of wave measurements from the Van Allen Probe satellites with differing resolutions to allow closer inspection of the larger amplitude waves, and their potential implications for energetic electron dynamics in radiation belt modelling. Particularly, the work investigates how the underlying variability of the waves may alter our interpretations of their properties.