

How Does Solar Wind Control Earth's Radiation Belt Dynamics?

S. Chakraborty, A. Lalti, O. Allanson, J. K. Sandhu, R. Desai.

10:00 – 10:30		Tea & Coffee
Session 1 (Chairs: Suman Chakraborty, Oliver Allanson)		
10:30	Welcome	
10:35	Samuel Wharton University of Leicester	The SMILE Mission and Earth's Radiation Belts - Invited
10:55	Sarah Glauert British Antarctic Survey	Solar Wind Driving in Radiation Belt Models - Invited
11:15	Dylan Weston Northumbria University	Using Solar Wind Parameters for Real Time Modelling of the Outer Radiation Belt - Invited
11:35	Ahmad Lalti Northumbria University	Solar Magnetic Configuration Control over Radiation Belt Electrons
11:50	Shannon Killey Northumbria University	Understanding Solar Wind Driven Characteristics of the Inner-Magnetosphere through Variability of the X-ray and UV Aurora
12:05	Bhagyashri Sathe Mullard Space Science Laboratory, UCL	Classifying Radiation Belt Increases and Decreases Using Solar Wind and Geomagnetic Parameters through Contingency Table Analysis
12:20	Open Discussion	
12:30 – 13:25		Lunch
Session 2 (Chairs: Ahmad Lalti, Ravindra Desai)		
13:25	Adnane Osmane University of Helsinki	From Solar Wind Forcing to Radiation-Belt Response: Uncovering the Physics of Radial Transport - Invited
13:45	Jonny Rae Northumbria University	Storm-time Alfvén speed gradients: the missing physics in radial diffusion models
14:00	Jasmine Kaur Sandhu University of Leicester	ULF wave - cold plasma coupling & impacts on the radiation belts
14:15	Yihui Tong University of Warwick	Modelling October 2024 extreme solar storm and radiation belt flux drop-out events
14:30	Shannon Killey Northumbria University	Typical Energetic Electron Pitch Angle Distributions: Evolution During Geomagnetic Storms
14:45	Oliver Allanson University of Birmingham	Diffusion Coefficients for Resonant Relativistic Wave-Particle Interactions Using the PIRAN Code
15:00	Suman Chakraborty Northumbria University	Cross-scale Wave Coupling and Energy-Dependent Modulation of Energetic Ion and Electron Populations in the Outer Radiation Belt
15:15	Open Discussion	
15:25	Closing Remarks	

Abstracts

The SMILE Mission and Earth's Radiation Belts (Invited)

Samuel Wharton¹, Jenny Carter¹

¹University of Leicester

The SMILE mission began in May 2026 to help better understand the coupling between the solar wind, magnetosphere and ionosphere. It carries four instruments: a magnetometer, the light ion analyser, the ultraviolet imager and the soft X-ray imager. Its 51-hour polar orbit gives the satellite a unique vantage point to observe the Earth's magnetosphere for long durations of time. SMILE has the potential to add to our understanding of radiation belt dynamics too. The radiation belts represent a key space weather hazard and are subject to a variety of acceleration and loss mechanisms, including magnetopause shadowing. SMILE's soft X-ray imager can be used to observe the dynamic motion of the magnetopause which forms the outer boundary of the radiation belts. SMILE's magnetometer operates at 40 Hz and will take measurements as the spacecraft passes through the radiation belts. In this talk, I will summarise the SMILE mission and explain how its data can be used to advance our understanding of the radiation belts.

Solar wind driving in radiation belt models (Invited)

Sarah Glauert¹

¹British Antarctic Survey

Predicting the behaviour of the radiation belts is an important part of protecting the satellites that orbit through them. Physics-based models, like the BAS Radiation Belt Model (BAS-RBM), adopt a Fokker-Planck approach to simulate the highly dynamic belts, with diffusion coefficients and loss timescales characterising the various processes within the belts. These processes include wave-particle interactions with both VLF and ULF waves, collisions with the atmosphere and losses to the magnetopause and are typically included as statistical models that are location, energy and geomagnetic activity dependent. Historically the geomagnetic activity has mainly been parameterised by ground-based indices (e.g., Kp, AE). I will discuss the reasons for this and then outline more recent work, including the use of solar wind parameters, highlighting when and where this can improve the modelling.

Using Solar Wind Parameters For Real Time Modelling of the Outer Radiation Belt (Invited)

Dylan Weston¹, I. J. Rae¹, A. W. Smith¹, C. E. J. Watt¹, S. Killey¹, K. R. Murphy²

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Energetic particles within the Van Allen radiation belts pose a risk to spacecraft passing through the region, particles can penetrate the spacecraft's outer shell and charge internal surfaces leading to electrostatic discharges and the subsequent effects. Modelling and forecasting the radiation belts is therefore key for both scientific and spacecraft protections perspectives. Many existing models aim to predict the exact value of electron fluxes found within this region, whilst warnings issued by space weather forecasters to stakeholders are often done on a threshold basis. The VAMPIRE model framework has been shown to accurately predict if the maximum ~2MeV flux levels will exceed set percentile thresholds using only geomagnetic indices and solar wind speed from the previous week, however these indices are not always available in real time. We present a radiation belt modelling pipeline of several machine learning models that first uses a Long Short-Term Memory network (LSTM) to now/hindcast geomagnetic conditions using only the solar wind measurements taken by spacecraft at L1. The resulting geomagnetic indices are then fed into a suite of random forest classifiers that can accurately predict whether 1.8MeV electron fluxes will exceed any of five percentile thresholds for L-shells between 3 and 6, and GEO. We find that this framework achieves balanced accuracies above 0.7 for nowcasting, with most forecasts maintaining balanced accuracies above 0.6 even at a 6-day lead time, longer than most operational models provide. This pipeline therefore makes reliable, real-time modelling of the outer radiation belt possible, using solar wind data.

Solar Magnetic Configuration Control over Radiation Belt Electrons

Ahmad Lalti¹, Jonathan Rae¹, Clare Watt¹, Stephanie Yardley¹, Savvas Raptis²

¹Northumbria University; ²John Hopkins University

Earth is surrounded by two highly dynamic concentric belts of particle radiation. The outer radiation belt exhibits coherent variability at solar-cycle, seasonal, and 27-day (Carrington) timescales. While the solar-cycle and Carrington variations have been attributed to the recurrence of coronal hole solar wind, the seasonal variation has long been explained by local geometric effects that modulate the solar wind-magnetosphere coupling. Here, we challenge this paradigm by showing that the periodic recurrence of coronal hole solar wind likewise drives the seasonal variation. We further demonstrate that the Alfvénic nature of this solar wind is responsible for the observed electron flux enhancement in the outer radiation belt. These findings provide a unifying framework linking solar magnetic topology, solar wind properties, and magnetospheric dynamics across multiple timescales at Earth and beyond.

Understanding solar wind driven characteristics of the inner-magnetosphere through variability of the X-ray and UV aurora

Shannon Killey¹, I.J. Rae¹, S. M. Petrinec²

¹Northumbria University; ²Lockheed Martin Advanced Technology Center

The Solar wind can drive intrinsic changes to the behaviour of energetic particles in the radiation belt, changes of which can enhance electron loss processes. When particles have sufficiently small pitch angles, falling within the loss cone, the trapped Van Allen particles can be lost to the ionosphere. Solar wind driving impacts particle precipitation by increasing the scattering of particles into the loss cone, enhancing probability of loss to the atmosphere. Bremsstrahlung interactions between precipitating electrons and atmospheric particles result in the emission of the X-ray aurora. While excitation of atmospheric particles drives the UV auroral oval, where its poleward boundary is typically defined as the open-closed field line boundary, which is highly variable due to solar wind driving. Using available Polar Ionospheric X-ray Imaging Experiment (PIXIE) observations (1996-2002) and Polar's Ultraviolet Imager (UVI), we investigate variability of the X-ray and UV auroral emissions during storm-time periods of extreme solar wind driving. We use the UV auroral emissions to provide insight to the solar wind control of the magnetosphere while the X-ray auroral missions are a proxy for the conditions of the radiation belts.

Classifying radiation belt increases and decreases using solar wind and geomagnetic parameters through contingency table analysis

Bhagyashri Sathe¹, Colin Forsyth¹, Andrew Fazakerley¹, Clare Watt², Alex Boyd³, Frances Staples⁴

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Radiation belt dynamics are well known to be driven by a combination of solar wind driving and geomagnetic activity. Current models use parameterisations of various conditions in geospace based on these drivers, but these parameterisations are somewhat arbitrary, potentially mixing conditions which are related to increases and decreases in the intensity of the radiation belts. To address this limitation, we identify large-scale increases and decreases in radiation belt electron content between 2012 and 2017 and use contingency tables to determine threshold values of solar wind parameters and geomagnetic indices that can best discriminate between periods of enhancements or loss. Our analysis identifies solar wind velocity and proton density averaged over the enhancement or loss period, alongside geomagnetic indices AL, AE and Dst, act as the best isolated discriminators of these changes, although the distributions of these average values show a large overlap. When this classification is attempted on 3-hour timescales (the limit of the cadence of the radiation belt content data), the performance of these indices drops significantly. By applying Empirical Mode Decomposition (EMD) to filter high-frequency variability in TRBEC moderately improves the results but does not match the performance when the start and end points were predefined. This suggests that while average solar wind and geomagnetic activity levels are useful for separating net acceleration and loss intervals in the radiation belts, identifying the causes of the starts of these intervals is critical.

From Solar Wind Forcing to Radiation-Belt Response: Uncovering the Physics of Radial Transport (Invited)

Adnane Osmane¹

¹University of Helsinki

Understanding how solar-wind variability drives Earth's radiation belts require not only characterising the forcing but also identifying the physical processes that govern the system's response. In this talk, I will examine radial transport from this perspective, focusing on how confidently we can distinguish the processes responsible for observed radiation-belt evolution.

I will first discuss recent evidence for universal scaling behaviour in radiation-belt dynamics, suggesting that common physical principles may organise particle acceleration and transport across very different magnetised environments. I will then present observational evidence of mesoscale phase mixing, which raises the question of whether signatures of particle redistribution can always be uniquely interpreted in terms of diffusive transport. Finally, I will discuss new theoretical developments revisiting the classical Schulz–Lanzerotti description of radial diffusion. Starting from a more general formulation of radial transport, the classical equation emerges only under particular assumptions, while the more general dynamics can retain an explicit dependence on particle phase space.

Together, these results motivate a closer examination of the transport physics connecting solar-wind forcing to radiation-belt response, and of how that physics is represented in models used to interpret and predict radiation-belt dynamics.

Storm-time Alfvén speed gradients: the missing physics in radial diffusion models

Jonny Rae¹, Kyle R. Murphy^{1,2}, Dylan J. Weston¹, Clare E.J. Watt¹, Jasmine K. Sandhu³

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Radial diffusion driven by Ultra-Low Frequency (ULF) waves is the central transport process in the outer radiation belt, and accurate specification of diffusion coefficients as a function of external and internal conditions is essential for credible radiation belt modelling. Existing models parameterise diffusion coefficients as a function of solar wind conditions and geomagnetic activity, with the radial dependence typically captured through a power law in L or L^* . Critically, however, the radial gradient of ULF wave power – and hence of the diffusion coefficient itself – is physically set by the gradient in the Alfvén speed profile, which undergoes dramatic restructuring during geomagnetic storms. This fundamental point is largely absent from the radiation belt modelling literature, although some work does implicitly include this (e.g., Murphy et al., 2023). During storm main phase, Earth's ring current intensification suppresses the local magnetic field whilst heavy ion loading increases plasma mass density, acting in concert to suppress the Alfvén eigenfrequency continuum and permitting lower-frequency ULF waves to penetrate to significantly lower L^* , directly modifying the spatial dependence of diffusion coefficients in a way that cannot be captured by Kp-based models such as Brautigam and Albert (2000). Although the Murphy et al. (2023) model implicitly captures some of this gradient variation, no current model explicitly accounts for the storm-time evolution of the Alfvén speed profile as a physical driver of the radial dependence of D_{LL} . Until models treat this as a time-dependent physical constraint, storm-time radial transport will remain systematically misrepresented.

ULF wave - cold plasma coupling & impacts on radiation belt dynamics

Jasmine Kaur Sandhu¹, T. K. Yeoman, M. K. James, T. Elsdén, A. N. Wright, I. J. Rae, A. W. Degeling, K. R. Murphy

¹University of Leicester

ULF wave driven radial diffusion plays a key role in the energisation, loss, and transport of radiation belt electrons. But what regulates when and where ULF waves exist in the inner magnetosphere? The cold plasma population coexists with radiation belts in the inner magnetosphere, and the cold plasma mass density controls how ULF waves propagate through the region, their polarisation, and where they deposit their energy. During geomagnetic storms, the structure and mass density of the cold plasma is intensely distorted and drastically modifies the ULF wave – cold plasma coupling.

Using remote observations of global cold plasma imaging combined with ground magnetometer array measurements of ULF waves, we identify how cold plasma structures can alter the polarisation of the waves. As well as being associated with storm-time plasmaspheric plumes in the afternoon sector, dawn side features such

as plasmaspheric shoulders also prove to be important. The discussion is placed in the context of radiation belt dynamics, where we will explore implications for electron energisation. Overall, we demonstrate that cold plasma dynamics are an important source of uncertainty in ULF wave processes and radiation belt dynamics, and understanding cold plasma-ULF wave coupling is a critical area of future investigations.

Modelling October 2024 extreme solar storm and radiation belt flux drop-out events

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¹University of Warwick

The radiation-belt electron flux exhibits dramatic variations across a range of spatial and temporal scales, including global-scale radial transport, mesoscale injections, and micro-scale wave-particle interactions. Long-term variability has been successfully captured by solving the Fokker Planck diffusion equation (e.g., BAS-RBM), incorporating energy, pitch-angle and radial diffusion imposed upon semi-empirical Tsyganenko magnetic field models. However, during geomagnetic storms, non-diffusive processes become significant. Dropouts in the electron flux, across several orders of magnitude, are often observed in the outer radiation belt during the early phases of geomagnetic storms, hampering accurate modelling of the subsequent few days where forecasts are needed the most. In this study, we employ global magnetohydrodynamic and test-particle (MHD-TP) simulations to investigate the dropout mechanisms.

We first examine the extreme storms of October 2024 where aurora was observed over the UK and show how global MHD simulations can realistically capture the dynamic magnetospheric response. We evaluate how key global MHD metrics respond to different solar wind inputs, including OMNI, STEREO-A. These metrics include the cross-polar cap potential (CPCP) and geomagnetic Kp indices derived from modelled ground magnetic field disturbances.

We then focus on a geomagnetic storm 2014, where the radiation belt flux was remarkably lost down to 4 Earth radii. We show how the pitch angle dependent last-closed drift shell (LCDS) can be significantly inward of the magnetopause and dynamically varies as the magnetopause contracts and expands. We calculate the Roederer L value by drift-shell tracing in the MHD magnetic field and use it to determine the time-dependent outer boundary of trapped radiation-belt electrons. This enables us to compare MHD particle simulations with radial diffusion calculations.

Typical Energetic Electron Pitch Angle Distributions: Evolution During Geomagnetic Storms

Shannon Killey¹, I. J. Rae¹, A. W. Smith¹, S. N. Bentley¹, C. E. J. Watt¹, S. Chakraborty¹, L. G. Ozeke², M.-T. Walach³, J. K. Sandhu⁴, D. Rasinskaite¹

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Energetic electron dynamics in the Van Allen Radiation Belts are governed by processes driven by the solar wind that can simultaneously drive acceleration, transport and loss. However, each individual process can be linked to a specific energy-dependent pitch angle distribution (PAD). We employ a novel, unsupervised machine learning (ML) technique on 7-years of Van Allen Probe Relativistic Electron-Proton Telescope data and discover that six PADs successfully describe 93% of outer belt relativistic electrons, two each of: pancake, butterfly, and flattop. Applications of the ML tool on Magnetic Electron and Ion Spectrometer data reveals 94% of outer belt sub-MeV electrons are described by three common PAD shapes: either flattop or one of two pancake morphologies. We investigate the occurrence and storm-time evolution of each PAD through 45 geomagnetic storms. We find new populations of PADs, including: "shadowing-like" and wave-particle interaction signatures at low-L, and radial diffusion and substorm injections at higher-L, as well as determining that wave-particle interaction dominated PADs are swamped by radial diffusion processes through geomagnetic storms. Our results clearly demonstrate that PAD characterization is a key component of understanding Van Allen radiation belt electron dynamics.

Diffusion Coefficients for Resonant Relativistic Wave-Particle Interactions Using the PIRAN Code

Oliver Allanson¹, Kappas, T., Tyrrell, J., Cunningham, G. S., Brown, M., Garcia, A., Watt, C., Chakraborty, S., Ratliff, D., Rae, J., Bentley, S., Elvidge, S., Themens, D.

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Quasilinear diffusion coefficients can be used to model the response of charged particles to resonant wave-particle interactions. The calculation of these coefficients is sufficiently complicated and arduous to render it prohibitive to many potential users, because of the expense in time spent developing the code. The PIRAN software package ("Particles In ResonANce") is written using Python and allows the user to calculate local and bounce-averaged relativistic diffusion coefficients in energy and pitch-angle space via the two main current proposed methods in the literature. The code is predominantly based upon the formalisms and methods presented in Glauert and Horne (2005, <https://doi.org/10.1029/2004JA010851>) and Cunningham (2023, <https://doi.org/10.1029/2023JA031703>). We solve for diffusion coefficients using exact relativistic formulae. We use Gaussian spectra in wave frequency and in tangent of the wave normal angle and solve the full cold-plasma dispersion relation. At present the code supports fully tested calculations for electron diffusion coefficients based on whistler-mode waves in a fully ionized proton-electron cold plasma. However, the codebase architecture is built such that future developments to include other wave modes and other plasma compositions should involve incremental additions. The initial release of PIRAN may not have the same number of features as some other numerical codes, but it has the advantages of being a fully open-source diffusion coefficient code that: (a) supports calculation of both local and bounce-averaged diffusion coefficients via both of the two proposed methods; (b) is written fully in Python; (c) has detailed user pages, commit history and changelog on GitHub.

Cross-scale Wave Coupling and Energy-Dependent Modulation of Energetic Ion and Electron Populations in the Outer Radiation Belt

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Coordinated spacecraft and ground-based observations provide evidence of cross-scale wave coupling and energy-dependent modulation of energetic ion and electron populations in the outer radiation belt. Using observations from Van Allen Probe B during 1030 UT – 1100 UT on April 20, 2018, we show that fast-mode compressional Pc5 ultra-low frequency (ULF) waves were excited in the outer radiation belt ($5 < L < 5.5$) in the post-midnight sector ($2.7 < \text{MLT} < 3.1$) near the magnetic equator ($\text{MLAT} < 5^\circ$), with a dominant periodicity of ~ 200 s. During this interval, electron and ion temperature anisotropies were elevated (> 1.2), favoring growth of both whistler-mode chorus and He⁺-band electromagnetic ion cyclotron (EMIC) waves. Additionally, the ULF waves drove periodic in-phase modulations of electron and ion fluxes in the 10s–100s keV energy range, which produced periodic variations of both chorus and He⁺-band EMIC waves at the same periodicity, connecting fluid and ion- and electron-gyroscale electromagnetic phenomena, spanning six orders of magnitude in frequency (mHz–kHz). The calculated pitch angle diffusion coefficients exhibited similar periodic variations in phase with the chorus wave power, suggesting strong pitch angle diffusion. Periodic ionospheric absorption measured by the riometer at the Rabbit Lake station, which was located closest to the magnetic footprint of Van Allen Probe B, independently confirmed the resulting electron precipitation signatures. Collectively, these results demonstrate a coherent, multi-step causal chain linking compressional ULF wave excitation to atmospheric electron precipitation through cross-scale wave coupling, with significant implications for radiation belt electron dynamics and upper atmospheric chemistry.