# Royal Astronomical Society Specialist Discussion Meeting

## Planetary Ultra-low Frequency Waves – Theory, Modelling and Observations

Friday, 11th March, 1030-1530 GMT, UTC

Format: Online only

| **10:30 (GMT, UTC)** | **Meeting Introduction** | |
|---|---|---|
| **10:35** | Martin Archer | *Surface, fast magnetosonic, and Alfvén waves in high-resolution global MHD simulations* |
| **10:55** | Shahbaz Chaudhry | *Global dynamic network response of Pc2 and Pc3 waves to the 2015 St Patrick's day storm using SuperMAG and Intermagnet ground-based magnetometers* |
| **11:10** | Hongyang Zhou | *Magnetospheric Responses to Solar Wind Pc5 Density Fluctuations From 2D Hybrid Vlasov Simulation* |
| **11:25** | Lucile Turc | *Global hybrid-Vlasov simulations of foreshock waves and their transmission into the dayside magnetosphere* |
| **11:40** | **15 min Break** | |
| **11:55** | David Southwood | *On the Detectability of Field Line Resonance* |
| **12:10** | Matt James | *What on Earth do 3D Field Line Resonances Look Like? Searching for 3D FLRs in Ground Magnetometer Data.* |
| **12:25** | Andrew Wright | *Evolution of High-m Poloidal Alfvén Waves in a Dipole Magnetic Field* |
| **12:40** | **40 min Lunch** | |
| **13:20** | Theodoros Sarris | *Using flux oscillations in the ULF range of frequencies as indicators of ongoing radial transport processes in the Earth's magnetosphere* |
| **13:35** | Theodoros Sarris | *On the distribution of ULF wave power in magnetic latitude in the inner magnetosphere* |
| **13:50** | Andy Smith | *Magnetosphere-Ionosphere Coupling at Substorm Onset Through ULF Waves* |
| **14:05** | **15 min Break** | |
| **14:20** | Xueling Shi | *Geoelectric and geomagnetic fields driven by magnetospheric ULF waves* |
| **14:40** | Jason Derr | *Stability Analysis of Interchange-Stable Plasma Sheet to ExB Shear Flow at Substorm Onset* |
| **14:55** | Li-Jen Chen | *Solitary magnetic structures developed from ULF Waves gyro-resonant with solar wind ions at Mars and Earth* |
| **15:10** | Simone Di Matteo | *ULF magnetospheric waves in response to solar wind periodic density structures* |

# List of Abstracts

**Martin Archer** (Invited) - Imperial College London
*Surface, fast magnetosonic, and Alfvén waves in high-resolution global MHD simulations*

System-scale magnetohydrodynamic (MHD) waves within Earth's magnetosphere are often understood theoretically using box models. While these have been highly instructive in understanding many fundamental features of the various wave modes present, they neglect the complexities of geospace such as the inhomogeneities and curvilinear geometries present. At present, only global MHD simulations can self-consistently reproduce the surface, fast magnetosonic, and Alfvén waves within a realistic equilibrium magnetosphere. In this talk we summarise recent progress in outer magnetospheric ULF waves from high-resolution global MHD simulations of the magnetospheric response to solar wind impulses. We demonstrate how the structure of magnetopause surface waves excited on the dayside is controlled by the inhomogeneous conditions, leading to Kelvin-Helmholtz amplified surface waves as well as body waves (waveguide modes and field line resonances) throughout the magnetosphere. We also show how polarisation properties of these large-scale waves are significantly altered by the realistic magnetosphere in ways that box and axially-symmetric dipole models do not capture. Finally, we discuss potential observational signatures in space and on the ground.

**Shahbaz Chaudhry** - University of Warwick
*Global dynamic network response of Pc2 and Pc3 waves to the 2015 St Patrick's day storm using SuperMAG and Intermagnet ground-based magnetometers*

Networks based on signal cross-correlation provide an efficient framework to characterize the temporal correlation between multiple time-series. We present a dynamical network analysis on 1s data from the full set of 100+ ground-based magnetometer stations collated by SuperMAG and Intermagnet, to capture the spatially correlated Pc2 and Pc3 response to the 2013 St Patrick's day geomagnetic storm. The time-varying network network is obtained from the windowed cross-correlation between all station pairs, using the methodology of Dods et al. 2015, 2017 and Orr et al. 2019, 2021. The network is constructed following band-pass filtering to isolate the Pc2 and Pc3 bands. A network connection between a pair of stations then corresponds to cross correlation between them that exceeds a threshold. At storm onset, we see a large negative excursion in DST/SMR and the Pc response is globally spatially correlated, with both short-range and long range (stations separated by MLT$>$ 9) connections in the network, and the network remains almost fully connected for about 10 mins. AE/SME become strongly enhanced about 2 hrs later when Bz IMF turns negative, the network becomes highly connected locally across Canada/northern US which at that time is located near midnight, directly under the auroral electrojet. The network continuously tracks variation in local and global correlation in Pc activity connection throughout the storm. Network connectivity does not simply track Pc power, which on average is enhanced at onset but then decays away, and in particular is not sensitive to the enhancement on AE/SME. Hence the Pc cross-correlation network provides additional information to Pc wave power. Network parameters may then offer a new method to quantify the local and global spatially coherent dynamics of storms.

**Li-Jen Chen** - NASA/GSFC
*Solitary magnetic structures developed from ULF Waves gyro-resonant with solar wind ions at Mars and Earth*

Solitary magnetic structures in the foreshock of Mars and Earth exhibit pulse-like magnetic field and density enhancements along with plasma heating and local solar wind (SW) ion reflection. The structures at Mars resemble the foreshock structures developed from ultra-low-frequency electromagnetic waves gyro-resonant with SW ions at Earth, and propagate toward the magnetosphere. We perform fully kinetic simulations to reproduce the solitary structures and the nonlinear evolution of ion distribution functions, illustrating their resonance with SW ions. The structures present self-induced foreshock turbulence that can have space weather effects. Our results advance the fundamental understanding of how SW interacts with planetary magnetospheres, and have potential impact on the current picture of planet-origin ion escape.

**Jason Derr** - Rice University
*Stability Analysis of Interchange-Stable Plasma Sheet to ExB Shear Flow at Substorm Onset*

The shear flow-interchange instability is proposed as the initiating mechanism behind substorm onset. ULF waves occurring within minutes of substorm onset are observed in the magnetotail at frequencies similar to those of the auroral beads, which are a result of a near-earth magnetospheric instability initiating current disruption in the plasma sheet. Growth rates were statistically determined as a function of wavenumber by Kalmoni et al. (2015) using ASI data from a set of substorm events. The RCM-E provides growth phase-evolved runs of background fields for stability analysis of a magnetospheric wave equation for shear flow-interchange modes derived in Derr et al. (2019), from which growth rates and dispersion relations can be calculated for comparison with the statistically determined growth rates and frequencies of the beads. In the plasma sheet, interchange and shear flow represent a competition between Kelvin-Helmholtz instability and overall interchange stability. On average, flux-entropy increases with radial distance. As the growth phase proceeds, the middle plasma sheet becomes nearly interchange stable, but flux-entropy decreases sharply at the inner edge. Destabilizing shear is weak in the middle of the sheet but quite strong in the SAPS region, earthward of the inner edge. We examine the conditions under which shear can overwhelm interchange stability to trigger instability. Instability phenomenology will be discussed in detail, including discussion of Doppler-resonance structure and a dimensionless parameter W* for characterizing stability domains. Mapping spatial properties to the ionosphere along field lines allows for comparison of instability wavelengths with those of the beads. All substorms terminate in relaxation, either because higher order nonlinearities ultimately suppress growth or due to external conditions which alter the background fields to suppress nonlinear growth. If higher order amplitude expansion terms contribute negatively at some order, then nonlinear relaxation occurs, and a method for determining field saturation values is established.

**Matt James** - University of Leicester
*What on Earth do 3D Field Line Resonances Look Like? Searching for 3D FLRs in Ground Magnetometer Data.*

Terrestrial field line resonances (FLRs) are typically considered to materialize as the global toroidal oscillation of an entire L-shell of an approximately axisymmetric magnetosphere. Recently, 3D simulations of Alfvén waves have shown that resonances are able to cross L-shells in non-axisymmetric magnetospheres and can exhibit non-toroidal polarizations while doing so. One situation where such 3D FLRs could appear is where a resonance crosses the density enhancement associated with a plasmaspheric plume. This study aims to use ground magnetometer data in conjunction with in-situ electron density data from the Van Allen Probes to elucidate the ground-based polarization signature of 3D FLRs.

**Simone Di Matteo** - Catholic University of America / NASA-GSFC
*ULF magnetospheric waves in response to solar wind periodic density structures*

Differentiating multiple types of Ultra Low Frequencies (ULF) waves at discrete frequencies (f<≈4 mHz) is challenging due to the many possible generation mechanisms and the ability to robustly identify such perturbations. On November 9, 2002, the Earth's magnetosphere interacted with two interplanetary shocks followed by a train of ≈90 min solar wind periodic density structures. In both the solar wind density and magnetospheric field observations, we separated broad power increases from waves at specific frequencies using a recently developed spectral analysis procedure. For the waves at discrete frequencies, we used the combination of satellite and ground magnetometer observations to identify differences in frequency, polarization, and observed magnetospheric locations. The magnetospheric response was characterized by: (i) forced breathing by periodic solar wind dynamic pressure variations below ≈1mHz; (ii) a combination of directly driven oscillations and wave modes triggered by additional mechanisms between ≈1 and ≈4 mHz.

**Theodoros Sarris** - Democritus University of Thrace
*Using flux oscillations in the ULF range of frequencies as indicators of ongoing radial transport processes in the Earth's magnetosphere*

One of the prevalent mechanisms for acceleration and transport in the Earth's magnetosphere is radial diffusion, caused by the resonant interaction between energetic electrons and ultra-low frequency (ULF) waves. We discuss  a novel indication of this resonant interaction: the appearance of periodic flux oscillations of 100s keV to few MeV electrons. These oscillations are drift-periodic flux fluctuations and have distinct characteristics from the more commonly observed drift echoes following storm- or substorm-related energetic particle injections. The amplitudes of such flux oscillations is dependent on a number of parameters, such as the local phase space density gradients, the amplitude of ULF waves and the width of electron detector energy channels. In particular, the energy width of electron detectors is a critical parameter affecting the observed amplitude of flux oscillations, with narrower widths enabling the observation of higher-amplitude flux oscillations; this potentially explains why such features were not observed regularly before the Van Allen Probes era, as previous spacecraft generally had lower energy resolution. We present simulations and observations demonstrating the dependence of the observed flux oscillations on various parameters and we discuss how such flux oscillations could be used as indicators of radial transport rates.

**Theodoros Sarris** - Democritus University of Thrace
*On the distribution of ULF wave power in magnetic latitude in the inner magnetosphere*

Ultra-low frequency (ULF) waves are known to radially diffuse hundreds-keV to few-MeV electrons in the magnetosphere, via drift-resonant interactions. Most current expressions quantifying radial diffusion via the radial diffusion coefficients are based on estimates of the power of ULF waves that are either made from spacecraft close to the equatorial plane or from the ground. In this study a statistical analysis of the distribution of ULF wave power in magnetic latitude is presented, and it is found that the wave power of the magnetic field significantly increases away from the magnetic equator. This result could have significant implications for the radial diffusion rates as currently estimated.

**Xueling Shi** (invited)
*Geoelectric and geomagnetic fields driven by magnetospheric ULF waves*

Geomagnetic perturbations related to various phenomena in the near-Earth space environment can induce geoelectric fields within the electrically conducting Earth. In turn these geoelectric fields drive geomagnetically induced currents (GIC) that can cause potential damage to technological infrastructure. Ultra-low frequency (ULF) waves have recently been reported to be one of the common sources of intense geoelectric fields during geomagnetic storms. Though numerous past studies have examined ULF wave related geomagnetic fields from a space weather perspective, few studies have linked ULF waves with geoelectric fields due to limited direct measurements of these fields. Using 1-second cadence geoelectric field measurements made at recently available magnetotelluric survey sites distributed widely across the United States, we explore the relationship between ULF waves and intense geoelectric fields. Detailed case studies demonstrate that the ULF wave driven geoelectric fields has significant spatial variation in contrast to a relatively uniform geomagnetic field perturbations, consistent with spatially varying Earth conductivity. We further show that geoelectric fields driven by magnetospheric ULF waves during geomagnetic storms have comparable amplitudes to once-per-century geoelectric hazard maps. Our results highlight the need for more research characterizing geoelectric fields driven by ULF waves.

**Andy Smith** – University College London
*Magnetosphere-Ionosphere Coupling at Substorm Onset Through ULF Waves*

Azimuthal structuring is usually observed within the brightening auroral substorm onset arc; such structure has been linked to the exponential growth of electromagnetic ultralow-frequency (ULF) waves. We present a case study investigating the timing and frequency dependence of such ULF waves on the ground and in the near-Earth magnetotail. In the magnetotail, we observe an increase in broadband wave power across the 10- to 100-s period range. On the ground, the arrival times spread from an epicenter. The onset of longer period waves occurs first and propagates fastest in latitude and longitude, while shorter periods appear to be more confined to the latitude of the onset arc. The travel time from the spacecraft to the ground is inferred to be approximately 1–2 min for ULF wave periods between 15 and 60 s, with transit times of 60 s or less for longer period waves. This difference might be attributed to preferential damping of the shorter period waves, as their amplitude would take longer to rise above background levels. These results have important consequences for constraining the physics of substorm onset processes in the near-Earth magnetotail and their communication to the ground.

**David Southwood** - Space and Atmospheric Physics, Blackett Laboratory, Imperial College London
*On the Detectability of Field Line Resonance*

Localised highly transverse polarised narrow band magnetic oscillations observed in a magnetosphere are normally attributed to standing Alfvén waves and are called field line resonances (FLR). The best evidence for a spacecraft encountering FLRs might seem detection of highly sinusoidal transverse polarised signals. This would be true in the plasma rest frame but what is seen by a moving spacecraft is more complex. Fundamental to the resonance process is the one-way transfer of energy from the other compressional hydromagnetic mode and it has long been known that inherent to the energy absorption process is spatial phase variation from magnetic shell to shell in the FLR vicinity. We use 3-D numerical simulation solutions of the cold plasma MHD equations in a dipole background field to examine observational signatures of FLR detectable on a moving spacecraft. On the moving spacecraft, the spatial structure appears in the time domain with the result that the signal frequency is changed. Moreover, as the expected phase structure varies from magnetic component to component, the simulation even predicts that components of the same signal measured on a moving spacecraft will have different frequencies. This provides a variety of interesting apparent anomalies that can also be distinguishing features in analysing data from a spacecraft magnetometer flying through FLR regions. Using a model where there are multiple FLRs excited with a system pumped with a single frequency, we shall show that the resonances lock in phase and amplitude is distributed with inverse dependence on the local gradient in FLR frequency across magnetic shells. The spatial phase variation has the same inverse dependence. Thus, somewhat ironically, the distinctive frequency shift is most easily seen in the vicinity of the smallest amplitude resonance. We shall illustrate with examples using magnetometer measurements from the final polar orbits of Cassini.

**Lucile Turc** - University of Helsinki, Finland

*Global hybrid-Vlasov simulations of foreshock waves and their transmission into the dayside magnetosphere*

The foreshock, extending upstream of the quasi-parallel portion of Earth's bow shock, is home to intense wave activity in the ultra-low frequency (ULF) range. Foreshock "30-second" waves, named after their typical period at Earth, are thought to be the main driver of ULF wave activity in the Pc3 range (10 – 45 s) observed routinely in the dayside magnetosphere. A handful of case studies with suitable spacecraft conjunctions have allowed simultaneous investigations of the wave properties in different geophysical regions, but the global picture of the wave transmission from the foreshock into the magnetosphere is still not known. In this study, we analyse global 2D simulations performed with the hybrid-Vlasov model Vlasiator to investigate Pc3 wave activity in near-Earth space. The simulations enable us to study the waves in their global context, and compare their properties in the foreshock, magnetosheath and dayside magnetosphere, for different sets of upstream solar wind conditions. Inside the magnetosphere, we focus on compressional Pc3 waves, because the 2D geometry of our simulation prevents the development of field-line resonances. We find that the upstream Alfvén Mach number impacts strongly the wave power in all geophysical regions. As expected, the distribution of wave power in the dayside magnetosphere is primarily controlled by the orientation of the upstream magnetic field, which determines the position of the foreshock. Dawn-dusk asymmetries tend to be larger for higher Alfvén Mach number. We discuss the implications of these results for the transmission of foreshock waves across the different geophysical regions.

**Andrew Wright** - University of St Andrews

*Evolution of High-m Poloidal Alfvén Waves in a Dipole Magnetic Field*

We investigate how initially high-m, poloidal Alfvén waves evolve using a numerical model solving the ideal, cold, linear magnetohydrodynamic (MHD) equations in a 2-D dipole coordinate system. The curved magnetic geometry provides a key difference between the poloidal and toroidal Alfvén

frequencies of any one field line. A polarization rotation from poloidal toward toroidal predicted from the Cartesian box model theory still occurs but now with the waves following contours of Alfvén frequency, which moves the Alfvén wave across field lines. The structure of these contours depends on the harmonic mode along the field line and the equilibrium. We find that the amplitude peak of the poloidal mode moves significantly radially outward in time. When the typically observed azimuthal phase motion of such waves is included, hodograms show a polarization rotation from purely poloidal to a mixed poloidal/toroidal polarization at all locations. Such features could be used to help interpret satellite observations of Pc4-5 poloidal ultralow frequency (ULF) waves in Earth's magnetosphere.

**Hongyang Zhou** - University of Helsinki
*Magnetospheric Responses to Solar Wind Pc5 Density Fluctuations From 2D Hybrid Vlasov Simulation*

Ultra-low frequency (ULF) waves in the Pc5 range, with periods between 150 – 600 s, play a key role in the dynamics of Earth's magnetosphere, in particular through their interaction with radiation belt electrons. One important source of magnetospheric Pc5 waves are fluctuations of the upstream solar wind parameters in the same frequency range. Pressure variations in the solar wind are thought to result in a forced breathing of the magnetosphere, as the magnetosphere would expand and compress in response to the changing upstream conditions, which drives ULF waves inside the magnetosphere. The details of the interaction of these solar wind variations with the Earth's bow shock and magnetosheath, their impact on the magnetosheath plasma properties and how the fluctuations would change before reaching the magnetopause, remain however unclear. In this study, we investigate the influence of externally-driven density variations in the near-Earth space using global 2D simulations performed with the hybrid-Vlasov model Vlasiator. The new time-varying boundary setup in Vlasiator allows us to set Pc5 periodic density pulses coming from the upstream. The density pulses cause the breathing motion of the bow shock, create clear stripes of variations inside the magnetosheath, and modulate the electromagnetic ion cyclotron (EMIC) and mirror modes. We characterize the spatial-temporal variations of waves on the simulation plane within the magnetosheath and discuss the potential impact on the near-Earth environment.