RAS Specialist Discussion Meeting: Towards the Most Accurate Substorm Onset Timing: Methods and Accuracy

Friday 11 December 2026 | 10:30–15:30

Venue: Royal Astronomical Society, Burlington House
Piccadilly, London W1J 0BQ, United Kingdom

Time	Programme
10:30–10:35	Welcome and introduction
10:35–11:00	Steve Milan Is substorm onset random?
11:00–11:25	Jonathan Rae Onset is a process, not an instant: the case for physics-based substorm onset timing
11:25–11:50	Ishbel Carlyle When does substorm onset begin? The case for mini-beads as the earliest auroral signature
11:50–12:15	Liisa Juusola Substorm onset signatures in ground-based magnetic field observations
12:15–13:15	Lunch break
13:15–13:40	Colin Forsyth Lessons learned from a solar cycle of SOPHIE
13:40–14:05	Andy Smith Magnetosphere-Ionosphere Coupling at Substorm Onset Through ULF Waves
14:05–14:30	Simon Walker Unlocking Earth's Radio Response to Substorms Through Auroral Kilometric Radiation
14:30–14:55	Siyuan Wu Auroral Kilometric Radiation as a Remote Probe of Auroral Acceleration and Substorm Dynamics
14:55–15:30	General discussion

Talk 1 | 10:35–11:00

Is substorm onset random?

Steve Milan

University of Leicester, UK

Abstract

A key aim of magnetospheric science is understanding the cause and timing of substorm onset. To address this, we examine statistically the duration of substorm growth phases which occurred during the year 2010. We find that there is no strong link between the duration of a growth phase and the average dayside reconnection rate during that growth phase. Rather, there is a distribution of growth phase durations between 10 mins and 3 hours, with a mean of 80 mins. We infer that substorm onset occurs randomly within this distribution, irrespective of the level of solar wind driving. Such a "typical" growth phase duration explains why the open magnetic flux content of the magnetosphere at substorm onset depends on average on the dayside reconnection rate. We also infer that the rate of nightside reconnection during the expansion phase closely matches the dayside rate at the time of substorm onset. This leads to a substorm intensity that is related to the open flux at onset, as has been observed in previous studies. We suggest that pseudo-breakups are failed substorm onsets and that the growth phase continues until one of these attempts to initiate nightside reconnection eventually succeeds.

Talk 2 | 11:00–11:25

Onset is a process, not an instant: the case for physics-based substorm onset timing

Jonathan Rae

Northumbria University, UK

Abstract

Every substorm onset time is, in practice, a detection time: the instant a growing signal crosses the sensitivity threshold of a particular instrument and method. But onset is a process, not an instant. Some timing methods measure that process directly, and some of the signals they rely on are closely related in time and space. I will argue that the most accurate onset times come from fitting exponential growth of co-located, correlated, near-identical optical and Ultra-Low Frequency (ULF) signals from ground-based auroral and magnetic observatories. Auroral beads and ULF waves begin at the same time and in the same location, the ionospheric ULF epicentre, and grow exponentially at the same rate. This indicates that both are signatures of a single plasma instability in the near-Earth magnetotail. Since the growth is exponential, any detection-based onset time depends on instrument sensitivity: at typical growth rates of around 0.05 s^{-1}, a tenfold gain in sensitivity moves the detected onset earlier by close to a minute. Fitting the exponential growth and extrapolating back to its start removes this dependence, and agreement between two independently measured signals provides a direct measure of timing accuracy. I will close with the implications for existing onset catalogues, which rely on different observables, and the opportunities offered by new high-resolution instruments.

Talk 3 | 11:25–11:50

When does substorm onset begin? The case for mini-beads as the earliest auroral signature

Ishbel Carlyle

Northumbria University, UK

Abstract

Determining when substorm onset begins is central to discriminating between competing models of the substorm trigger. Auroral beads, wave-like structures along the onset arc, are the most widely used optical marker of onset and are consistent with kinetic Alfvén waves (KAWs), yet the timing of their appearance is limited by the resolution of conventional all-sky imagers (ASIs). We analyse a substorm observed by a co-located ASI and a narrow-field imager with nearly four times finer spatial resolution and fifteen times faster cadence. The narrow-field data reveal "mini-beads": fine-scale wave structures embedded within the onset arc that propagate eastward alongside the larger beads far earlier than traditional auroral beads. Given that mini-beads are detectable approximately one minute before onset can be identified in the ASI data, this implies that the onset instability is already growing before conventional imaging can resolve it. Mapped to the magnetotail, both mini-beads and beads lie deep within the dispersive KAW regime ($k_\perp \rho_i \approx 20–80$ and 2–6, respectively), yet mini-beads propagate about 5.6 times faster. The perpendicular scale alone cannot explain this difference, which points instead to distinct parallel wavenumbers, source regions, or nonlinear evolution. Mini-beads are therefore the earliest auroral signature of onset yet identified, and suggest that onset times derived from conventional imaging may potentially and systematically lag the true start of the instability.

Talk 4 | 11:50–12:15

Substorm onset signatures in ground-based magnetic field observations

Liisa Juusola

Finnish Meteorological Institute, Finland

Abstract

Substorms are a commonly occurring but insufficiently understood form of dynamics in the coupled magnetosphere-ionosphere system, associated with geomagnetic disturbances and auroras. We have analyse the behavior of ionospheric equivalent currents around substorm onsets identified by Frey et al. (2004). The equivalent currents were derived from IMAGE magnetometer observations using the spherical elementary current system (SECS) method, and local auroral observations were provided by all-sky cameras. We found that the equivalent current dynamics around the onset can typically be described by three structures: a channel of poleward equivalent current (wedgelet) associated with bursty bulk flows by previous studies), a westward electrojet (WEJ) associated with an auroral arc, and a vortex. Depending on its polarity, the vortex either indents the WEJ and arc equatorward or bulges the WEJ poleward while winding the arc into an auroral spiral. In addition, there may be a background current system associated with the large-scale convection. The SECS method also provides the large-scale geoeletric field associated with the geomagnetic variations. The geoelectric field drives detrimental geomagnetically induced currents (GIC) in electric power transmission grids. Preliminary results from a statistical analysis covering the years from 1999 to 2025 indicate that substorms may be the most significant driver of intense geoelectric field peaks in the evening sector.

Talk 5 | 13:15–13:40

Lessons learned from a solar cycle of SOPHIE

Colin Forsyth

Mullard Space Science Laboratory, University College London, UK

Abstract

The SOPHIE substorm detection algorithm was put forward as a way to identify substorm growth, expansion and recovery phases based on the SuperMAG SML index. Using the SMU index, the algorithm seeks to flag events which bear a resemblance to enhanced convection. Since publication in 2015, it has been widely used, particularly in the UK community. It is, however, not unique as a way of identifying substorms from geomagnetic indices. In this talk, we explore some of the lessons learned from the use of SOPHIE in identifying substorms and other forms of geomagnetic activity.

Talk 6 | 13:40–14:05

Magnetosphere-Ionosphere Coupling at Substorm Onset Through ULF Waves

Andy Smith

Northumbria University, UK

Abstract

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.

Talk 7 | 14:05–14:30

Unlocking Earth's Radio Response to Substorms Through Auroral Kilometric Radiation

Simon Walker

Dublin Institute for Advanced Studies, Ireland

Abstract

Auroral kilometric radiation (AKR) provides a valuable diagnostic of magnetospheric dynamics, particularly during substorms. Using a decade of observations (1995–2004) from the WIND spacecraft, we investigate how the frequency structure of AKR evolves throughout the substorm cycle. We introduce an adaptive method to identify low- and high-frequency extensions (LFEs and HFEs) of AKR and examine their occurrence and contribution to integrated radio power as a function of substorm epoch and magnetic local time.
We find that frequency extensions occur most frequently around substorm onset and in the pre-midnight sector. LFEs exhibit a particularly strong response, contributing an increased fraction of total AKR power following onset, suggesting a distinct substorm-driven emission component. In contrast, HFEs show weaker

and less systematic variations. Furthermore, substorm onsets identified through auroral imagery reveal clearer AKR signatures than those derived from ground magnetometers. These results highlight the potential of AKR frequency extensions as a diagnostic of substorm onset and evolution.

Talk 8 | 14:30–14:55

Auroral Kilometric Radiation as a Remote Probe of Auroral Acceleration and Substorm Dynamics

Siyuan Wu

University of Southampton, UK

Abstract

Auroral kilometric radiation (AKR) is generated in auroral acceleration regions and is closely associated with energetic electron precipitation. Its variability has long been linked to auroral dynamics and magnetospheric substorms. However, the physical interpretation of many AKR signatures and their relationship to substorm evolution remain poorly understood. Because AKR is emitted near the local electron gyrofrequency, its emission frequency provides information about the magnetic field strength and altitude of its source. Broadband AKR observations can therefore probe the spatial extent and temporal evolution of radio sources along auroral magnetic field lines. This offers a means of remotely investigating auroral acceleration regions beyond the local perspective available from single-point measurements. In this talk, I will present recent progress in understanding AKR variability and its relationship to substorm dynamics. I will discuss what these observations reveal about auroral acceleration and assess their potential for monitoring global magnetospheric dynamics.