From heliophysics to space weather forecasts

Richard Harrison, **Jackie Davies** and **Jonny Rae** summarize progress in capitalizing on UK expertise in research and instrumentation for new space weather forecasting – the subject of an RAS Discussion Meeting in March.

The term "space weather" describes the effects of solar-generated phenomena – in particular coronal mass ejections (CMEs), stream interaction regions (SIRs) and solar energetic particles (SEPs) – on human technological systems and health. Our escalating reliance on technology has made space weather a topic of mounting concern to governments and agencies worldwide over the past decade. This is evidenced in the UK in particular by an increase in awareness, investment and infrastructure. For example, there has been significant UK investment in the space weather elements of the European Space Agency's (ESA's) Space Situational Awareness (SSA) programme (recently rebranded as Space Safety) established in 2009; indeed, the UK has been the largest investor in SSA Period 3. Since 2011, severe space weather has been included on the UK's Risk Register of Civil Emergencies, which has in turn led to the installation of the UK Met Office Space Weather Operations Centre (MOSWOC), operating in parallel with the US Space Weather Prediction Centre (SWPC).

Meeting aim

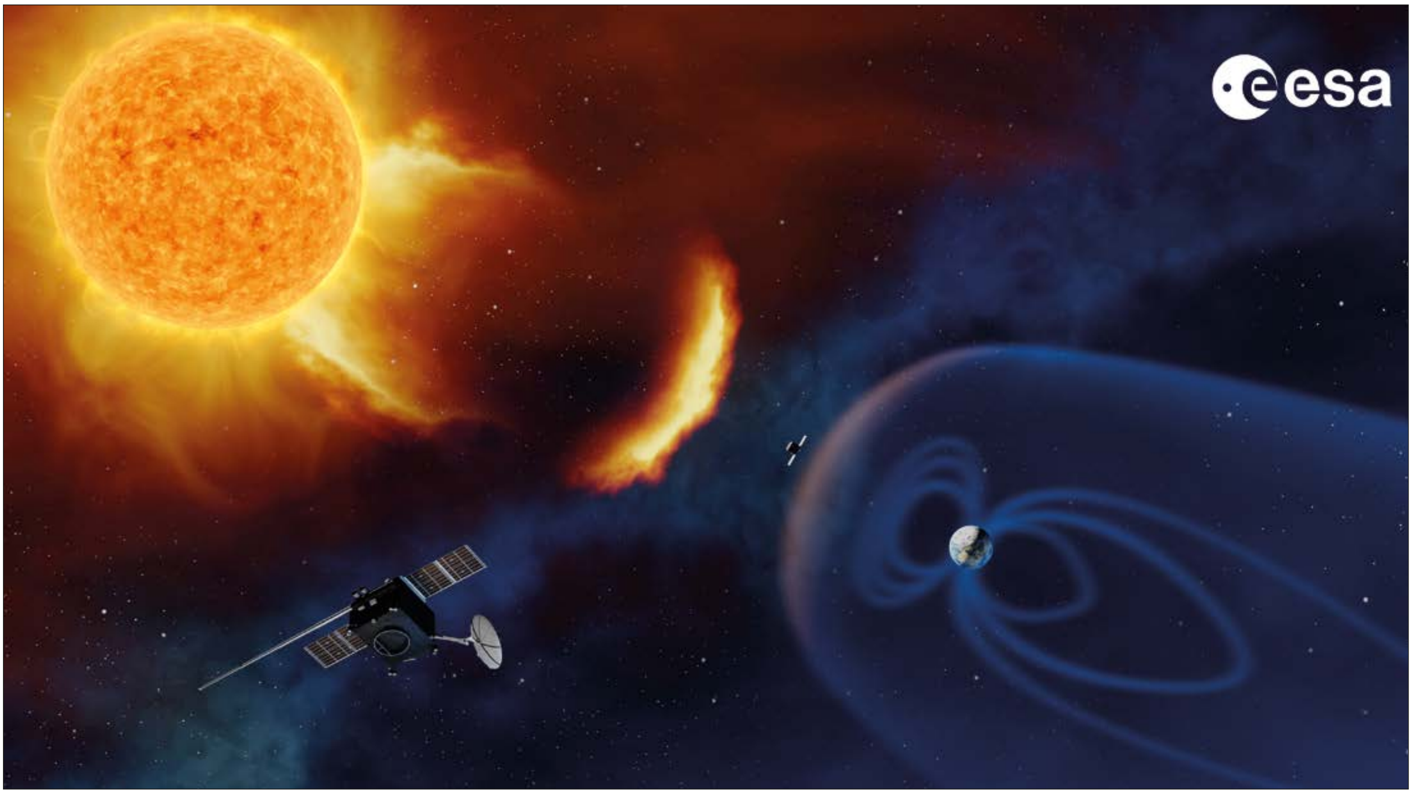
Forecasting the impact of space weather phenomena on technological systems, with the aim of mitigating their effects, is still in a stage of relative infancy, particularly when compared to terrestrial weather forecasting. Such forecasting is highly reliant on ongoing scientific research, including model development, as well as mainly relying on scientific instrumentation that is not optimized for real-time usage. Bridging the gap between scientific research and instrumentation in heliophysics and the development of operational space weather services was the subject of an RAS Discussion Meeting held at Burlington House on 8 March 2019: Transitioning Research and Instrument Expertise in Heliophysics into Space Weather Monitoring Capabilities at L1 and L5.

The UK boasts a world-class heliophysics programme, in terms of both scientific research and the underpinning instrumentation. Note that we define heliophysics as the study of the effects of the Sun on the solar system, including the corona and heliosphere and the magnetospheres and ionospheres of the planets, including Earth. The UK's international standing in this field is exemplified by leadership in missions such as ESA's Cluster, Solar and Heliospheric Observatory (SOHO) and Solar Orbiter missions, the latter due for launch next year, and NASA's Solar Terrestrial Relations Observatory (STEREO). Investment in these missions has resulted in major advances in our understanding of the physics of our Sun and its effects. Although these are scientific missions, it has been long understood that observations and experience gleaned from missions such as these is critical for both furthering our understanding of the science of space weather effects, but also, as noted above, underpins current space weather forecasting endeavours.

> **"Although these are scientific missions, they underpin space weather forecasting"**

Since extreme space weather was included in the UK Risk Register of Civil Emergencies in 2011, the UK has been at the forefront of activities to develop an effective approach to space weather mitigation. A major element of this has been the UK's commitment to the Space Weather (SWE) and more recent Lagrange (LGR) segments of ESA's SSA programme. LGR focuses on the design and development of a dedicated space weather monitoring mission to the L5 Lagrange point (60° behind the Earth in its orbit), to operate in conjunction with a US-led mission to the L1 point (1.5 million km sunward of Earth). The ESA L5 mission, known as Lagrange, is nearing the end of its Phase A/B1 study. The Phase A/B1 activities comprise parallel industry-led studies of the Lagrange platform – headed by Airbus Defense and Sapce (ADS), UK, and OHB System AG, Germany – and development studies of the remote-sensing and *in situ* instrument packages, led by RAL Space and the Mullard Space Science Laboratory (MSSL) respectively.

It is, hence, timely to assess how best to coordinate the complementarity of the research and operational aspects of the UK's heliophysics programme. To that end, the meeting was aimed at the transitioning of research and instrumental expertise acquired from our involvement in recent and ongoing space science missions into



1 An artist's impression of the ESA Lagrange mission (foreground) stationed at the L5 point. The accompanying NASA/NOAA (National Oceanic and Atmospheric Administration) spacecraft at L1 is also shown. The image depicts a CME directed towards Earth. (ESA)

operational space weather capabilities that would, in particular, support the development and, subsequently, the exploitation of the Lagrange L5 mission (particularly in conjunction with its L1 counterpart).

The large audience for the meeting, filling the RAS Lecture Theatre, was a reflection of its timeliness. After an initial welcome by the conveners, the first session of the meeting was intended to give an overview of the ESA space weather activities, and the Lagrange mission activities in particular. The first talk, "ESA SSA and Space Safety space weather activities", was given by **Juha-Pekka (Jussi) Luntama**, head of the Space Weather Office of ESA's Space Safety Programme Office. Luntama's presentation reviewed the SSA programme, which currently includes space surveillance and tracking, and near-Earth objects, in addition to space weather (both SWE and LGR) elements. He briefly discussed space weather impacts on infrastructure – including increased atmospheric drag on spacecraft, geomagnetically induced currents in power grids, spacecraft radiation damage and charging, and satellite navigation errors. Luntama went on to describe the SSA SWE activities within ESA, which are coordinated by the European Space Operations Centre (ESOC). The SWE activities include the five SSA Expert Service Centres in Solar Weather, Heliospheric Weather, Space Radiation, Ionospheric Weather and Geomagnetic Conditions, which provide forecasts, alerts, data and tools relevant to the end user domains. The ESA space weather portal (swe.ssa.esa.int) is the mechanism by which users can gain access to the service centre products.

While the SWE segment also includes activities related to small satellite and hosted payloads, the LGR segment activities are focused on the Lagrange mission to the L5 point, scheduled for launch in 2025. Luntama summarized the benefits of the L5 location, including (1) the ability to monitor evolving active regions on the Sun well before the time that they have rotated towards locations where they could potentially impact Earth, and (2) the ability of coronal and heliospheric imaging to image the passage of Earth-bound CMEs from an off Sun–Earth line perspective. The Lagrange Phase A/B1 activities are currently nearing completion, with a forthcoming bridging phase spanning the ESA Ministerial in November 2019 at which the project needs multinational endorsement to proceed. If adopted at the ESA Ministerial, the plan is that Lagrange will operate in conjunction with a complementary NASA/NOAA mission to L1 (figure 1).

> **"The plan is that Lagrange will operate with a complementary mission to L1"**

Lagrange instruments

Lagrange will host suites of remote-sensing and *in situ* instruments, with heritage from missions such as STEREO and Solar Orbiter. The remote-sensing instrument package Phase A/B1 study is being undertaken by an international consortium led by RAL Space, UK. **Jackie Davies**, consortium lead for the package, presented an overview of the design and capabilities of the four instruments that comprise the remote-sensing package: the Photospheric Magnetic Field Imager (PMI) led by the Max-Planck Institute for Solar System Research, Germany; the Extreme Ultra-Violet Imager (EUVI) led by the Centre Spatial de Liège, Belgium, and the Royal Observatory of Belgium; and the COROnagraph (COR) and Heliospheric Imager (HI) both led by RAL Space. It is expected that the four instruments will share a common data processing unit (DPU) – called the Image Processing and Control Unit (IPCU) – being developed by Airbus, Germany, albeit with a dedicated preprocessing unit for PMI because of the unique complexity of its on-board processing requirements. A team led by Deimos, UK, is developing an end-to-end simulator (E2ES) for the remote-sensing instrument package in order to support such activities as the definition of instruments via assessment of instrument performance and the definition of the IPCU. The UK Met Office, as the UK risk owner and service provider, provides oversight on behalf of the user community. While the instruments are, of course, being developed for space weather application, their heritage comes from science instruments such as the NASA STEREO HI instruments, the Sun Watcher using Active Pixel System Detector and Image Processing (SWAP) instrument on ESA's Proba-2, and the Polarimetric and Helioseismic Imager (PHI) on ESA's Solar Orbiter.

The consortium undertaking the *in situ* instrument package Phase A/B1 study is led by MSSL (UK). Consortium lead **Jonny Rae** presented an overview of the five *in situ* instruments: the fluxgate Magnetometer (MAG) led by Imperial College London, UK; the Plasma analyser (PLA) led by MSSL; the Medium Energy Particle Spectrometer (MEPS) led by the University of Kiel, Germany; the Radiation Monitor (RM) led by the Paul Scherrer Institute, Switzerland; and the X-ray Flux Monitor (XFM) led from Isaware, Finland. As for the remote-sensing instrument package, the philosophy of a common DPU is adopted, in this case being developed by the Institute of Atmospheric Physics of the Czech Academy of Sciences.

The two instrument suites have been designed to meet observational requirements that have been developed over several years and consolidated within Phase A of the current instrument studies.

Fluxgate magnetometer

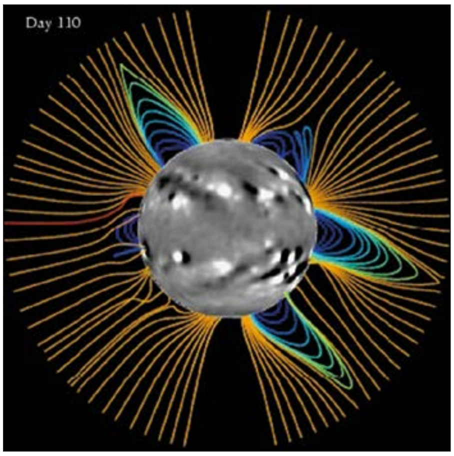
The MAG instrument on Lagrange was further discussed by **Jonathan Eastwood** (Imperial College London), who stressed the importance of measurements of the magnetic field strength and orientation at L5 for understanding the geoeffectiveness of large-scale transient (such as CME) and background (such as SIR) structures in the solar wind. Moreover, knowledge of the magnetic field configuration is critical to understanding energetic particle propagation via connectivity with the source population. The MAG instrument, which uses dual fluxgate sensors mounted on a boom to measure the magnetic field, is a collaboration between Imperial College London and the Space Research Institute, Graz. MAG is based on similar instruments on such scientific missions as JUpiter Icy Moons Explorer (JUICE), Solar Orbiter, Magnetic Multiscales Mission (MMS), BepiColombo, DoubleStar and Cluster; this high-heritage instrument can, hence, be considered low risk.

Results from the two parallel Lagrange platform Phase A/B1 studies were discussed in a joint presentation by **Marc Scheper** (OHB System AG, Germany) and **Tim Harris** (ADS, UK). In their talk "How to build a mission to L5", Scheper and Harris highlighted the particular challenges of launching a large, highly instrumented spacecraft – with an operational requirement to provide real-time observations with 99% availability even under extreme space weather conditions – into deep space. That said, it was also noted that the orbital configuration and fixed attitude requirements of Lagrange, as well as its synoptic observing programme, allow for a relatively simple, and hence stable, spacecraft design. The mission scenario presented involves a 14-month transfer to L5 and a communications strategy involving a traditional RF approach, with X-band high-gain antenna (HGA) and low-gain antenna (LGA), potentially augmented by an optical communication system that could provide data transfer to Earth at 10 times the rate of the HGA. The presentation concluded with Harris sharing experiences from ADS's recent integration of the Solar Orbiter payload onto the spacecraft.

The second session of the meeting, focusing on UK space weather strategy, began with a review of the role of the UK Met Office presented by **Mark Gibbs**, the Met Office's head of space weather. After the addition of severe space weather to the National Risk Register of Civil Emergencies in 2011, ownership of that risk was delegated by what is now the Department of Business, Energy and Industrial Strategy (BEIS) to the UK Met Office with the installation of the Met Office Space Weather Operations Centre (MOSWOC). Since April 2014, MOSWOC has been one of only two civil space weather forecasting centres worldwide that is operational 24 hours a day. Gibbs made the crucial point that, currently, most of the real-time forecasts of the arrival of solar wind structures at Earth are based on observations from aging scientific missions not optimized for the provision of real-time data (particularly SOHO and STEREO), highlighting the need for dedicated space weather missions such as Lagrange. Finally, he reported on the solar wind modelling activities being undertaken at MOSWOC, and their input data requirements. In particular, he highlighted the usage of photospheric magnetograms and coronagraph imagery in the modelling of the background solar wind and initial CME characteristics, respectively, as input to the so-called WSA–ENLIL magnetohydrodynamic model that is currently used to forecast the propagation of CMEs through the heliosphere, and predict their potential arrival at Earth. WSA refers to the Wang, Sheeley and Arge empirical model that employs photospheric magnetograms to generate a solar wind background on which the ENLIL magnetohydrodynamic code is run (see e.g. Millward *et al.* 2013 and references therein).

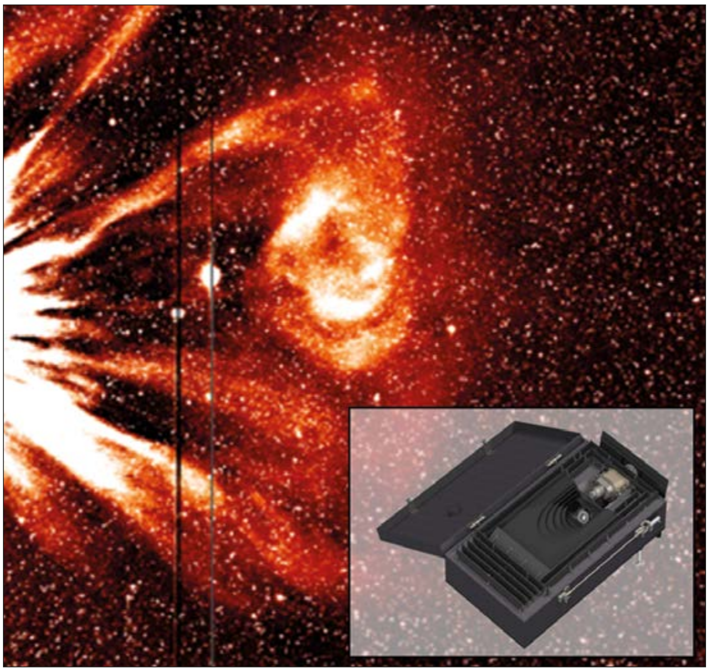
"The Lagrange L5 mission is considered to be a high priority by the UK government"

Then **Mario Bisi** (RAL Space) discussed national and international space weather priorities. Bisi's talk began with a diagram that illustrated the UK space weather strategy – showing the relationship between (1) UK government entities (government departments, including BEIS, and UKSA, the UK Space Agency), (2) the UK academic/research community (comprising universities, national laboratories and groups such as the UK Solar Physics [UKSP] and Magnetospheric, Ionospheric and Solar–Terrestrial [MIST] communities), (3) the provider of space weather services (the Met Office), and (4) other interested parties (such as UK industry). This demonstrates the wide range of organizations that need to coordinate in order to facilitate the development and operation of a national space weather programme. At the heart of UK space weather strategy lies the Space Environment Impacts Expert Group (SEIEG), comprising experts from the research and industrial communities. The aim of SEIEG is to advise government on space weather issues. Bisi emphasized an underlying philosophy of ensuring that we are prepared for space weather, rather than generating panic. To this end, efforts are being made to assess worst-case scenarios, including undertaking socio-economic studies thereof (see Eastwood *et al.* 2018, Oughton *et al.* 2018), and identifying areas that need further study. The fact that the Lagrange L5 mission is considered to be a high priority within UK government was also highlighted.



2 Image derived from the non-potential solar global magnetic field modelling of Mackay *et al.* (2016).

An overview of solar wind modelling at the Met Office, with a focus on exploitation of L5 data, was presented by **David Jackson** (UK Met Office). He introduced the general approach to forecasting solar wind/CME arrival at Earth that is adopted by the Met Office, that being the combined WSA–ENLIL model exploiting GONG (Global Oscillation Network Group) photospheric magnetograms and SOHO and/or STEREO coronagraph data. To demonstrate the added value of an L5 capability, he presented skill scores of background solar wind forecasts at Earth (forecast versus actual arrival) using a persistence model. He found that, generally, skill scores improved when data from L5 were used



3 A CME travelling through the inner heliosphere as viewed by the HI instrument on the STEREO-A spacecraft. The image is 20° × 20°, with the ecliptic plane running horizontally across its centre and with the Sun being 4° off the left-hand side of the image. The STEREO HI instrument is shown inset. (Eyles *et al.* 2009)

instead of the persistence model. Jackson subsequently discussed the benefit of extending the so-called CME Analysis Tool (CAT) – conventionally used to derive CME directions, speeds and size from SOHO and/or STEREO coronagraph imagery – to include HI data from STEREO (CAT-HI). Thereafter, he described the scenario in which photospheric magnetic field images are available from L5 in conjunction with analogous imagery from a near-Earth vantage point. Evidence suggests that this would lead to a marked improvement in CME arrival forecasts at Earth through improved background solar wind estimates. In summary, Jackson emphasized the fact that techniques to exploit L5 data from Lagrange, when available, are already in place and would provide improved forecasting capabilities.

The remaining contributions to the meeting were collected into a section entitled "Science and instrumentation", the aim being to provide a forum for an open discussion of scientific results, methods and instrumentation/mission concepts that could lead to practical advances in space weather. Naturally, the talks and posters covered a diverse range of topics.

Leon Golub (Harvard-Smithsonian Institute for Astrophysics, USA) reviewed space weather forecasting using wide-field EUV imaging, in particular relating to a proposal to mount the Coronal Spectrographic Imager in the EUV (COSIE) instrument on the International Space Station (ISS). EUV imaging is critical for ascertaining the level of solar activity, as it is sensitive to structures in the chromosphere and low corona; the COSIE concept provides wide-angle imaging of structures from disc centre out to beyond three solar radii, further than previous instruments. The main goals of COSIE are to enhance understanding of (1) the dynamics, including eruptions, of the hot, magnetized solar coronal plasma, (2) the transition between closed and open magnetic structures in the outer corona, and (3) the evolution of CMEs in the low corona. We have already got used to spectacular EUV images from the Atmospheric Imaging Assembly (AIA) instrument on NASA's Solar Dynamics Observatory (SDO); the sensitivity of COSIE would be around 500 times greater. If successful, COSIE will be installed on the ISS in 2023.

"So-called 'ghost fronts' can be used to infer the longitudinal structure of a CME"

Although **Duncan Mackay** (University of St Andrews) was, unfortunately, unable to attend the meeting in person, his presentation – demonstrating the additional value of photospheric magnetograms taken from an L5 vantage point for non-potential solar global magnetic field modelling – was displayed as a poster (figure 2). The model includes two coupled components, the first being a photospheric flux transport model, including flux emergence, which accurately reproduces the observed radial magnetic field strength on the Sun, and the second being a coronal magneto-frictional relaxation component that models quasi-static evolution. The study quantified the difference in the accuracy of global non-potential models between a simulation using photospheric magnetograms from L1 only and a simulation using magnetograms from both L1 and L5. Global quantities from the latter simulation were 26–40% better than those from a simulation based on L1 data alone, with an accuracy of 65–78% when compared to a reference Sun simulation; this is a significant improvement over the 46–57% accuracy achieved for simulations using L1 data only (see Yeates *et al.* 2008, Mackay *et al.* 2016).

Mat Owens (University of Reading) discussed assimilation of *in situ* solar wind measurements from L5. He began his talk by listing the strengths and weaknesses of current forecasting approaches, e.g. WSA–ENLIL. While acknowledging the strengths of such global reconstructions, including for modelling dynamic/transient structures such as CMEs, he pointed out shortcomings such as their inability to generate $\mathbf{B}_z$ (the north–south component of the interplanetary magnetic field, IMF) and the fact that the models, in general, impose no observational constraints beyond the corona. Owens asked whether co-rotation of the observed solar wind conditions, measured *in situ* at L5, could be combined with information from the photosphere and corona (as used in current forecasting) to provide an optimal solution, within the uncertainties of both the models and the data. He showed some encouraging results (see Lang & Owens 2018).

Observing SEP events

Owens went on to discuss combined L1/L5 measurements in the context of solar energetic particle (SEP) event forecasting. This presentation from **Timo Laitinen** (University of Central Lancashire), who was unable to attend, stressed the value of multispacecraft observations of SEP events, especially given the significant extent of some SEP events and the nature of their measured flux profiles in relation to CME topology. Some of the more advanced SEP propagation models were listed and it was noted that, for forecasting large events, all require multipoint observations, including measurements of their anisotropy and turbulence. After further discussion of SEP transport and turbulence, Owens summarized the significant benefits of combined L1/L5 measurements for forecasting SEP events.

Chris Scott (University of Reading) presented an analysis of STEREO HI imagery, where so-called "ghost fronts" were used to infer the longitudinal structure of a CME. Scott noted that HI images of CMEs frequently contain a wealth of structure (e.g. figure 3). He interpreted the structuring of the well-studied 12 December 2008 CME that is manifest in STEREO HI images in terms of the projection of discrete longitudinal sections of the leading edge of the CME. By comparing the relative position of the CME front and following ghost fronts seen in the images, with the locations of features determined from modelling three different CME morphologies, each expanding into a uniform background solar wind, he showed that the two fronts could be

Meeting posters

• **Eamon Scullion** (Northumbria University) described the Solar CubeSats for Linked Imaging Spectropolarimetry (SULIS) formation-flying CubeSat mission concept, which includes both Earth-orbiting and off Sun–Earth line spacecraft, with spectropolarimetric and coronagraphic imaging capabilities to address the science that underpins space weather. SULIS will target, in particular, the elusive 3D magnetic field in the corona.

• **Matthew West** (Royal Observatory of Belgium) presented an analysis of the Earth-directed CME of 17 October 2009, when the STEREO-B spacecraft was near L5, as a demonstrator of the advantages of an L5 observational capability. The CME could be continuously tracked through the fields of view of all STEREO remote-sensing instruments. West demonstrated that, using the L5 data, an improved and continuously updated estimate of the CME arrival time can be provided.

• **Gabriel Muro** (University of Aberystwyth) presented results from a Time-Normalized Optical Flow (TNOF) image processing method to map fine-scale flows in EUV images of the chromosphere/low corona from the AIA instrument on SDO. Muro suggested that the method could be adapted to use simultaneous L1 and L5 EUV observations for 3D flow mapping.

• **Richard Grimes** (University of Aberystwyth) presented a method for sunspot analysis, using Helioseismic Magnetic Imager (HMI) images from SDO. Grimes demonstrated the method on a complex sunspot group observed during September 2014, revealing a partial reversal in the rotation of the sunspots during a flare. The goal of the method is to provide information on the behaviour of sunspots and their surrounding environments in an effort to better understand the physics of solar magnetic fields and activity.

• **Llyr Humphries** (University of Aberystwyth) presented the results of a study of fan-shaped jets observed within a flaring active region using the NASA Interface Region Imaging Spectrograph (IRIS) EUV imaging spectrometer, which is in a polar Sun-synchronous Earth orbit. The study seeks to identify links between jet-like events and foot-point brightening and/or flaring events, with the aim of revealing key small-scale processes in the corona.

• **Richard Harrison** (RAL Space) presented a review of single-viewpoint and multi-viewpoint analysis of STEREO HI imagery over the last decade, with the particular aim of demonstrating the value of out of Sun–Earth line observations for space weather application (Harrison *et al.* 2017, 2018).

inferred to correspond to the expected position of the flank and nose of the CME. In the alternative scenario where the flank of the CME is expanding into a high-stream solar wind stream, the separation of the two fronts would be greater than expected from the simple uniform background solar wind configuration. Although further work is needed to consolidate these results, ghost fronts could provide more information about the longitudinal topology of CMEs.

Analysing a CME

The analysis of the evolution of a CME, based on *in situ* measurements taken by the NASA ACE (Advanced Composition Explorer), Wind, THEMIS (Time History of Events and Macroscale Interactions during Substorms) B and C and Juno spacecraft, was presented by **Emma Davies** (Imperial College London). The CME was detected *in situ* by Juno on 25 October 2011, during the spacecraft's cruise phase *en route* to Jupiter. The large magnitude of the CME magnetic field, and its orientation, caused a strong geomagnetic storm at Earth; the geoeffectiveness of the CME was due, in part, to the fact that it had partially merged with an earlier, slower CME. At the time of the event, Juno was close to radial alignment with the spacecraft at L1 (ACE and Wind) and near the Moon (THEMIS B and C). It was found, however, that the slight longitudinal separation between Juno and the near-Earth spacecraft resulted in clear and significant differences in detected signatures. Shock drivers such as CMEs can extend up to ~100° in longitude, illustrating the need for *in situ* measurements with a wide range of longitudinal separations. This case study demonstrated techniques that could be easily applied to coordinated L1 and L5 observations, to better understand CME evolution throughout the heliosphere.

> **"These techniques could be easily applied to coordinated L1 and L5 observations"**

Robertus Erdélyi (University of Sheffield) delivered a presentation on the ground-based Solar Activity Monitor Network (SAMNet). He started with a discussion on previous success in forecasting flaring and CME eruption from active regions, employing a weighted horizontal magnetic gradient method (see Korsós *et al.* 2015, 2019). This has led to a desire for a network of synoptic solar telescopes, using magneto-optical filter (MOF) technology, with a capability of making magnetic field measurements at different altitudes in the solar atmosphere. Thus, the SAMNet concept was conceived, with the first realization of the synoptic MOF instrumentation concept now set up at Gyula in Hungary.

The final oral presentation was given by **John Coxon** (University of Southampton), who reported on the results of a study on the response times of Birkeland currents to changes in the interplanetary magnetic field (IMF), published by Coxon *et al.* (2019). He argued that, while the timescales of Birkeland currents to react to southward turnings of the IMF are well understood, there is still controversy over response times to changes in $\mathbf{B}_y$ (the east–west IMF component). By analysing data from the AMPERE (Active Magnetosphere and Planetary Electrodynamics Response Experiment) spacecraft, Coxon *et al.* (2017) gleaned a number of important insights on the response times of Birkeland currents, namely (1) that timescales of response to changes in $\mathbf{B}_z$ are 10–20 minutes on the poleward edge of the dayside current ovals and 60–90 minutes on the equatorward edge, corresponding to the timescale for expansion of the polar cap, (2) that $\mathbf{B}_z$ timescales are 120–150 minutes on the nightside, consistent with substorm recurrence timescales and (3) that timescales to changes in $\mathbf{B}_y$ are 15–30 minutes on the dayside, indicative of direct driving from the solar wind, and up to 240 minutes elsewhere.

The meeting also included six contributed posters (see box "Meeting posters"). The conveners would like to thank all presenters and attendees for contributing to a very successful meeting, and would also like to thank the RAS's Siobhan Adeusi for her help with organizing the meeting. •

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MEETING DETAILS

The RAS Discussion Meeting, Transitioning Research and Instrument Expertise in Heliophysics into Space Weather Monitoring Capabilities at L1 and L5, was held at Burlington House on 8 March 2019.

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