Forecasting Solar Energetic Particles and Associated Eruptive Events
Abstract Booklet

Date: Friday 13th March 2022, 10:30 - 15:30 BST
Location: Virtual, Zoom Webinar

Meeting Abstract

Solar energetic particles (SEPs) are accelerated by magnetic reconnection-driven processes during solar flares and by CME-driven shocks. Large gradual SEP events, associated with high-energy protons (up to tens of GeV), can cause hazardous space weather conditions at Earth and hence pose a severe radiation risk for crewed spaceflight and a significant threat to near-Earth technological assets. To mitigate the risk posed by SEPs and solar eruptive events we must be able to forecast these events prior to their occurrence. Achieving this task is very difficult because it requires a multidisciplinary approach combining a broad range of remote and in-situ observations, data-driven modelling and simulations. One of the main issues is what input parameters, in particular magnetic field properties of source regions taken from solar observations, are required to improve forecasts provided by data-driven models. This is one of the aims of NERC's “SWIMMR Aviation Risk Monitoring” (SWARM) project.

In this meeting we aim to discuss the configuration and evolution of the solar magnetic field in the build-up to solar eruptive events as well as the production and propagation of solar energetic particles. What magnetic field parameters would be useful for the next generation of space weather models to predict solar energetic particles and their associated flares and coronal mass ejections? What effect do the solar and heliospheric magnetic fields have on the acceleration, injection and propagation of energetic particles? The timing of this meeting is particularly appropriate given the ongoing SWARM project and the availability of data from new missions such as Parker Solar Probe and Solar Orbiter.

Meeting Schedule

Time (BST)	Chairs: Stephanie Yardley & Charlotte Waterfall	
10:30	**Stephanie Yardley**	**Opening Remarks**
10:35	Natasha Jeffrey (Invited)	*Energetic electron acceleration during solar flares; at the Sun and in the heliosphere*
11:05	Nicolas Wijsen (Solicited)	*Modelling solar energetic particle events with EUHFORIA and PARADISE*
11:25	**Coffee Break**	
11:30	Kate Mowbray	*Particle Energisation in Collapsing Magnetic Traps*
11:50	Adam Hutchinson	*Simulating SEP propagation from a shock-like source using 3D test-particle simulations*
12:10	Christopher Davis	*Calculations of radiation dose rates in Earth's atmosphere during anisotropic solar energetic particle conditions*
12:30	**Lunch**	
	Chairs: Lucie Green & Silvia Dalla	
13:15	Beatriz Sanchez-Cano	*Solar Energetic Particles detected by BepiColombo*
13:35	Alessandro Bruno (Solicited)	*Empirical Model of 10 – 130 MeV Solar Energetic Particle Spectra at 1 AU Based on Coronal Mass Ejection Speed and Direction*
13:55	**Coffee Break**	
14:05	Katie Whitman (Invited)	*SEP radiation hazards from the perspective of astronauts and space travel*
14:35	Hazel Bain (Invited)	*Operational Forecasting of Solar Energetic Particles*
15:05	Stephanie Yardley & Charlotte Waterfall	*SEP Space Weather developments within the SWIMMR SWARM project*
15:25	**Lucie Green**	**Closing Remarks**
15:30	**End of Meeting**	

Abstracts

Operational Forecasting of Solar Energetic Particles (Invited)

Hazel M. Bain, CIRES CU Boulder/NOAA Space Weather Prediction Center
Coauthors:Robert Steenburgh, Terry Onsager

Particles accelerated in association with solar flares and coronal mass ejections can be seen at Earth as solar energetic particle (SEP) events. Forecasting SEPs with significant lead time can be challenging; predicting the evolution of particle intensities during an event is even harder. There have been improvements in our scientific understanding and modeling of solar eruptions and SEPs over the last decade which must now percolate into our operational forecast tools. In this presentation I will talk about the challenges of forecasting solar energetic particles in real time; discuss what observational inputs forecasters have available to them in the moment; give an overview of our current SEP forecasting skill at the NOAA Space Weather Prediction Center; and cover some ways in which people are working to improve our real time capabilities.

Empirical Model of 10 – 130 MeV Solar Energetic Particle Spectra at 1 AU Based on Coronal Mass Ejection Speed and Direction (Solicited)

Alessandro Bruno, CUA & NASA/GSFC
Coauthors: Ian G. Richardson

We present a new empirical model to predict solar energetic particle (SEP) event-integrated and peak intensity spectra, along with the times of peak intensity, between 10 and 130 MeV at 1 AU. The model is based on multi-point spacecraft measurements from the Solar TErrestrial RElations Observatory (STEREO), the Geostationary Operational Environmental Satellites (GOES), and the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) satellite experiment. The analyzed data sample includes 32 SEP events occurring between 2010 and 2014, with a statistically significant proton signal at energies in excess of a few tens of MeV, unambiguously recorded at three spacecraft locations. The spatial distributions of SEP intensities were reconstructed by assuming an energy-dependent 2D Gaussian functional form, and accounting for the correlation between the intensity and the speed of the parent coronal mass ejection (CME), and the magnetic-field-line connection angle. The CME measurements used are from the Space Weather Database Of Notifications, Knowledge, Information (DONKI). The model performance, including its extrapolations to lower/higher energies, was tested by comparing with the spectra of 20 SEP events not used to derive the model parameters. Despite the simplicity of the model, the observed and predicted event-integrated and peak intensities at Earth and at the STEREO spacecraft for these events show remarkable agreement, both in the spectral shapes and their absolute values.

Calculations of radiation dose rates in Earth's atmosphere during anisotropic solar energetic particle conditions

Christopher S. W. Davis, University of Surrey
Coauthors: Fan Lei, Alex Hands, Ben Clewer, Keith Ryden, Clive Dyer

Solar particles and cosmic rays traveling through the Earth's magnetosphere and atmosphere can induce high radiation doses in air crews, passengers, and aircraft electronics, particularly during the so-called Ground-Level Events (GLEs), where radiation doses can increase by orders of magnitude. To simulate radiation doses during these events, the MAIRE+ system has been under development at the University of Surrey as part of the MET office's SWIMMR N2 program. MAIRE+ is designed to predict current

particle-induced radiation dose rates in Earth's atmosphere in real-time through the modeling of particle trajectories in Earth's magnetosphere and secondary particle production in Earth's atmosphere. MAIRE+ assumes that solar particles arrive at Earth isotopically, an assumption that is often untrue during complex GLEs. Also, the Earth's magnetosphere is a complex and dynamic system, where magnetic conditions can fluctuate rapidly with both time and with solar conditions. This presentation will therefore discuss plans to upgrade the existing MAIRE+ physics model to incorporate anisotropy in the next version of MAIRE. A proper simulation of anisotropy will both increase the accuracy of dose calculations during a GLE and improve the determination of the solar energetic particle spectra from the global neutron monitor station data.

Simulating SEP propagation from a shock-like source using 3D test-particle simulations

Adam Hutchinson, UCLan

Coauthors: Silvia Dalla, Timo Laitinen, Charlotte, O. G. Waterfall

Gradual Solar Energetic Particle (SEP) events are thought to result from temporally extended acceleration at propagating Coronal Mass Ejection (CME)-driven shocks. Several models of SEP propagation after injection by a CME-shock have been developed within the framework of the focussed transport equation. They have been used to derive SEP time-intensity profiles at a number of observer locations.

In this work the first 3D full-orbit test-particle simulations including time-extended particle injection from a shock-like structure and propagation of these particles through interplanetary space are presented. We construct time-intensity profiles and anisotropies at 1.0 and 0.3 au for comparisons with observations from new missions, such as Parker Solar Probe and Solar Orbiter. Comparison of our results with those from focussed transport models show that corotation has an influence in the intensity profiles as particle-filled magnetic flux tubes no longer remain connected to a given observer. Anisotropies modelled from our code show sustained anti-sunward anisotropies during the initial phase of the event, until the shock passage. These are particularly clear for observers at 0.3 au, providing a useful reference for comparison with observations from Parker Solar Probe and Solar Orbiter.

Energetic electron acceleration during solar flares; at the Sun and in the heliosphere (Invited)

Natasha Jeffrey, Northumbria University

Coauthors: Ross Pallister, Morgan Stores

Solar eruptive events such as solar flares and coronal mass ejections (CME) are efficient particle accelerators and prime laboratories for studying astrophysical acceleration and transport processes. In recent years, our understanding of solar flare acceleration has been enhanced by (1) observationally-driven kinetic models with realistic transport effects and (2) multi-messenger diagnostics (remote and in-situ). Nonetheless, many questions remain about how and where particles are accelerated (e.g., the role of plasma turbulence and shocks), and how different the plasma environments (e.g., collisions in the dense solar corona, turbulence) affect their transport and hence, observed properties. Hard X-ray (HXR) observations provide a direct link to solar flare-accelerated electrons on closed magnetic loops at the Sun, while escaping solar energetic electrons (SEEs) into the heliosphere on open field lines can be detected in-situ at 1 AU and now at locations closer to the Sun with Parker Solar Probe (PSP) and Solar Orbiter (SolO). However, the connection between these distinct electron populations, their production and indeed their connecting magnetic topology, is still poorly understood, and often further complicated by secondary CME acceleration in the heliosphere. In this talk, I will review recent advances in understanding flare and CME particle acceleration, and discuss how the properties of the solar flare acceleration region can be constrained by tandem observations of energetic electrons at the Sun and in the heliosphere together, using remote sensing (e.g., X-rays, radio) and various in-situ observations, alongside state-of-the-art modelling in both plasma environments.

Particle Energisation in Collapsing Magnetic Traps

Kate Mowbray, University of St Andrews
Coauthors: Thomas Neukirch

Investigating the motion of charged particles in time- and space-dependent electromagnetic fields is central to many areas of space and astrophysical plasmas. Here we present results of studying the energy changes of particle orbits that are trapped in inhomogeneous magnetic fields with rapidly shortening field lines. These so-called collapsing magnetic trap (CMT) models can be useful for explaining the acceleration of particles below the reconnection region in a solar flare. For both 2D and 3D CMT models (e.g. Giuliani et al. 2005; Grady & Neukirch, 2009), betatron acceleration was considered to be the dominant energisation mechanism. We present new results that have been obtained using an improved version of the 3D CMT model by Grady and Neukirch (2009). Our investigations show that a sizeable portion of particle orbits can gain a significant amount of energy that is not explained by the betatron effect. The other mechanism at play appears to be Fermi acceleration at loop tops, where the particle passes through the region of field that is collapsing the most rapidly. We show that the particles that experience this effect the most have initial positions that are related to specific regions of the magnetic field model and it is these particle orbits whose energy gains are not adequately explained by betatron acceleration alone. In fact, some particle orbits seem to gain energy almost entirely as a result of this Fermi acceleration. One can also show that for suitable initial conditions the same effect can be seen in the 2D CMT model given by Giuliani et al. (2005). This updated understanding of the systems at play for particle acceleration in a CMT can, for example, inform any changes made to future CMT models by accounting for the large number of particles that see energy gains due to Fermi acceleration. So far, our models have only looked at particles that are trapped in orbits along closed field lines but we aim to broaden the scope of our model to also include particle orbits along open field lines.

Solar Energetic Particles detected by BepiColombo

Beatriz Sanchez-Cano, University of Leicester
Coauthors: Rami Vainio, Haruka Ueno, Marco Pinto, Philipp Oleynik, Satoko Nakamura, Aiko Nagamatsu, Go Murakami, Richard Moissl, Yoshizumi Miyoshi, Shoya Matsuda, Arlindo Marques, Arto Lehtolainen, Seppo Korpela, Emilia Kilpua, Rosie Johnson, Juhani Huovelin, Daniel Heyner, Wojtek Hajdas, Manuel Grande, Patricia Gonçalves, Eero Esko, Carlota Cardoso, Johannes Benkhoff

BepiColombo is a joint mission of the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA) to the planet Mercury, that was launched in October 2018 and it is due to arrive at Mercury in late 2025. It consists of two spacecraft, the Mercury Planetary Orbiter (MPO) built by ESA and the Mercury Magnetospheric Orbiter (MMO) built by JAXA. The cruise phase to Mercury will last ~7 years and constitutes an exceptional opportunity for investigating solar energetic particles. During the cruise phase, several instruments capable of detecting solar energetic particles are connected on a regular basis. These are the Solar Intensity X-Ray and Particle Spectrometer (SIXS) and the BepiColombo Environmental Radiation Monitor (BERM) on MPO, and the Solar Particle Monitor (SPM) on MMO. So far, BepiColombo has detected 15 solar particle events during the cruise, several of them at locations in the inner Solar System that provide excellent opportunities for multi spacecraft studies. One

such case is the recent solar event, which occurred on 28 March 2022 where BepiColombo was well aligned with STEREO-A in the Parker spiral, and almost linearly aligned with Earth. In this work, we compare the temporal evolution of the solar energetic particle event with BepiColombo observations and other missions, as well as we show the scientific potential of this planetary mission to investigate solar energetic particles during its cruise phase.

Solar Energetic Particles: A Space Radiation Hazard for Human Exploration Class Missions

Katie Whitman, NASA JSC SRAG

Solar energetic particles (SEP) are energized in difficult-to-predict eruptive events on the Sun that quickly flood the inner heliosphere with potentially hazardous radiation for humans and electronics in space. Current human space operations take place in Low Earth Orbit (LEO) inside of the Earth's protective magnetosphere. NASA's Artemis missions will return humans to the Moon and serve as a proving ground for missions to Mars. During these new Exploration Class missions outside of LEO, the human and vehicle will experience the full extent of each SEP event. This talk will describe the radiation hazard due to SEPs, the challenge of forecasting SEP events, and the planned approach foreseen by NASA's Space Radiation Analysis Group (SRAG) to manage the response to a radiation event.

Modelling solar energetic particle events with EUHFORIA and PARADISE (Solicited)

Nicolas Wijsen, KU Leuven

We present recent simulation efforts performed with the model named Particle Radiation Asset Directed at Interplanetary Space Exploration (PARADISE). This tool models the transport of solar energetic particles (SEPs) in the heliosphere by solving the time-dependent five-dimensional focused transport equation stochastically. This is done by evolving energetic particle distributions in a solar wind generated by the three-dimensional magnetohydrodynamic model EUHFORIA ('EUropean Heliospheric FORcasting Information Asset'). This latter model allows the injection of coronal mass ejections (CMEs) into the ambient solar wind, by using either a cone or a spheromak model to describe the CME structure. The coupling between PARADISE and EUHFORIA permits us to study the effect of a solar wind that deviates strongly from a nominal Parker-like configuration on the spatial, pitch-angle and energy dependencies of the energetic particle distribution function.

SEP space weather developments within the SWIMMR SWARM project

Stephanie Yardley, UCL & Charlotte Waterfall, UCLan

Forecasting solar energetic particle (SEP) events at high energies (e.g. >300 MeV for protons) is crucial as they pose the most chance of causing ground level enhancements (GLEs) and risk to humans and infrastructure in space. The rarity of relativistic SEP events make them difficult to forecast.

We first investigate the magnetic field configuration and connectivity of an active region that produces multiple SEP events during its disk passage in order to determine whether the magnetic field can be used to help predict the occurrence and arrival of SEPs.

We also extended SPARX, a currently operational SEP forecasting model, to forecast flux profiles for >300 MeV protons. The new high energy version of SPARX will be presented, producing flux profiles in three different energy channels up to 700 MeV, within minutes of being triggered by a large flare.