Solar flare acceleration signatures and their connection to solar energetic particles

Natasha Jeffrey (Team leader, University of Glasgow, UK)
Frederic Effenberger (Team Co-Leader, GFZ Helmholtz Centre Potsdam, Germany)

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Abstract

The Sun is an efficient particle accelerator. However, the relation between different energetic particle populations is not well-established. Observational studies during the RHESSI era demonstrated the still poorly understood existence of a connection between solar flare signatures of accelerated electrons at the Sun and the corresponding solar energetic particles (SEPs) detected at 1 au. A fundamental question then arises: can these distinctly observed electron populations come from the same flare-associated acceleration region and be drawn from the same population of electrons? Observational and theoretical studies alone cannot satisfactorily address this question. Therefore, we aim to combine state-of-the-art multi-instrument observations with kinetic modelling that simultaneously studies the acceleration and transport of flare-accelerated electrons toward and away from the Sun in the varying plasma conditions of the extended solar atmosphere. The model output will be compared with X-ray, radio, and in-situ measurements, allowing us to test whether both electron populations can indeed form within a single, but possibly extended, acceleration region with varying plasma properties. Simultaneous modelling of the escaping and precipitating electron populations will help to constrain the plasma properties of such a region (e.g., its size, temperature, density, turbulence); properties not currently constrained by remote flare observation alone. We will probe various electron transport mechanisms (collisional and non-collisional) in different parts of the solar atmosphere, and combine them with detailed interplanetary transport modelling and multi-spacecraft observations. This will lead to a greater understanding of the important physical processes that modulate the populations during their transport, helping us to study flare particle acceleration from multiple perspectives. The project is timely for the 2018 launch of the Parker Solar Probe.

1. Scientific rationale

Solar flares are an explosive product of magnetic energy dissipation in the Sun's atmosphere. Processes of energy release and transfer acting in flares, thought to be initiated by magnetic reconnection (e.g., Dungey 1953, Parker 1957, Sweet 1958, Priest & Forbes 2000), are widespread in high-energy astrophysics, but still poorly understood. Much of the magnetic energy is dissipated into the acceleration of high-energy electrons (e.g., Holman et al. 2011), possibly via turbulence (e.g., Larosa & Moore 1993, Petrosian 2012, Vlahos et al. 2016, Kontar et al. 2017), but other mechanisms such as shock acceleration may also contribute (e.g., Warmuth et al. 2009, Li et al. 2013). This acceleration is highly efficient, with a large proportion of the released energy thought to go into the production of deka-keV electrons (e.g., Emslie et al. 2012, Warmuth & Mann 2016, Aschwanden et al. 2017), possibly even in microflares (e.g., Glesener et al. 2017). However, the mechanisms, and even the locations of solar flare particle acceleration are still poorly understood, since many emission mechanisms are density-weighted, and so electrons often produce their strongest emission away from the primary site(s) of acceleration. In a standard flare model, electrons are accelerated along newly formed, closed magnetic field lines, and precipitate into the dense layers of the lower atmosphere where they lose energy (see, e.g. Holman et al, 2011 for a review), while other electrons escape into the heliosphere on open field lines, as solar energetic particles (SEP[1] see e.g., Klein & Dalla 2017). The most direct diagnostics of flare-accelerated electrons originate from their remote radiative signatures (X-rays, gamma-rays and radio emissions) and in situ measurement at 1 au. Recently, significant progress has been made in disentangling the properties of acceleration with that of complex transport effects that alter electron properties, both at the Sun (e.g., Kontar et al. 2011) and in the heliosphere (e.g., Dresing et al. 2014, Laitinen et al. 2016, Strauss et al. 2017). Although several studies (such as

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[1] The term SEP is a broad term that can denote electrons, protons and ions. In this project, we are primarily interested in electrons or SEEs (Solar Energetic Electrons).

Krucker et al. 2007) have compared the spectra and timing of flare-accelerated electrons detected at the Sun and at 1 au, further understanding of their complicated connection and studies of multiple electron transport mechanisms in varying plasma conditions requires a numerical approach, alongside multi-instrument observations. We will tackle the problem by applying a stochastic differential equation (SDE) method that can model the acceleration and transport of electrons in different solar and heliospheric environments. We apply this method because it constitutes a simple and versatile approach for modelling and testing multiple transport processes, while allowing us to easily visualise the physical processes involved in the transport process under investigation (Strauss & Effenberger 2017).

Importantly, in the last few years, there has been significant advancement in the understanding of electron transport, both at the Sun and the heliosphere. At the Sun, for many years, electrons were simply assumed to travel deterministically as field-aligned beams with little or no interaction with the surrounding plasma (cold thick-target (CTT), Brown 1971) until they reached the cold and denser layers of the chromosphere. However, multiple studies (e.g., Leach & Petrosian 1981, Kontar et al. 2014, Jeffrey et al. 2014, Bian et al. 2017, Musset et al. 2018) show that the initial injection properties, as well as diffusive processes in energy and pitch-angle, alongside deterministic processes, play a vital role in determining the electron properties and our interpretation of their properties. For example, previous studies that used a simplistic CTT approach could not constrain the power of flare-accelerated electrons at the Sun; which is a key parameter required for understanding flare acceleration. However, now, the recent inclusion of coronal plasma properties and energy diffusion (the warm-target collisional model, Jeffrey et al. 2014, Kontar et al. 2015) allows us to calculate an upper limit in the number and power associated with these electrons. Further, the inclusion of photon transport effects such X-ray albedo (e.g., Bai & Ramaty 1978) and radio wave scattering (e.g., Steinberg et al. 1971, Kontar et al. 2017) are equally vital for understanding the observed similarities and/or differences between different populations of flare accelerated electrons from remote observation. In the heliosphere, the turbulent solar wind can significantly influence the actual propagation of particles to 1 au. Here, we will employ the latest understanding of SEP transport modelling (e.g., Laitinen et al. 2018, Hu et al. 2017, 2018) including parallel and cross-field diffusion, and magnetic-field line meandering, to address the complex transport behaviour of particles from the Sun to Earth and to different spacecraft locations.

We have collected a team with significant expertise in solar and heliospheric modelling, theory, observations and instrumentation. Such a diverse team will allow the development of large-scale models capable of modelling electron acceleration and various transport effects, reproducing multi-flare and associated SEP observations.

2. Project goals

i. *To understand the connection between flare-accelerated electrons at the Sun and those detected in interplanetary space. A model will be developed that will be initially used to test if both the sunward and earthward electron populations can be reproduced with similar spectral and timing properties as seen from observation.*

After the 2002 launch of RHESSI (a solar-dedicated hard X-ray (HXR) imager/spectrometer; Lin et al. 2002), several studies attempted to examine the properties of flare-accelerated electrons at the Sun and at 1 au together. Krucker et al. (2007) compared RHESSI HXR spectra, a direct diagnostic of flare-accelerated electrons at the Sun, with WIND/3DP (Lin et al. 2005) in-situ electron spectra at 1 au[2] (Fig. 1). For prompt events, where the inferred release time coincides with the flare HXR burst, they found a clear systematic correlation of both the power-law spectral indices and of the total number of electrons, which is consistent with a single process accelerating both the escaping and HXR-producing electrons. However, several interesting questions emerged from this study: 1. why was there a weak correlation for events where the detection of electrons at 1 au is delayed compared to the HXR burst?

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[2] We note that spacecraft such as WIND are located at the Lagrangian point L1, in orbit around the Sun at 0.99 au≈1 au.

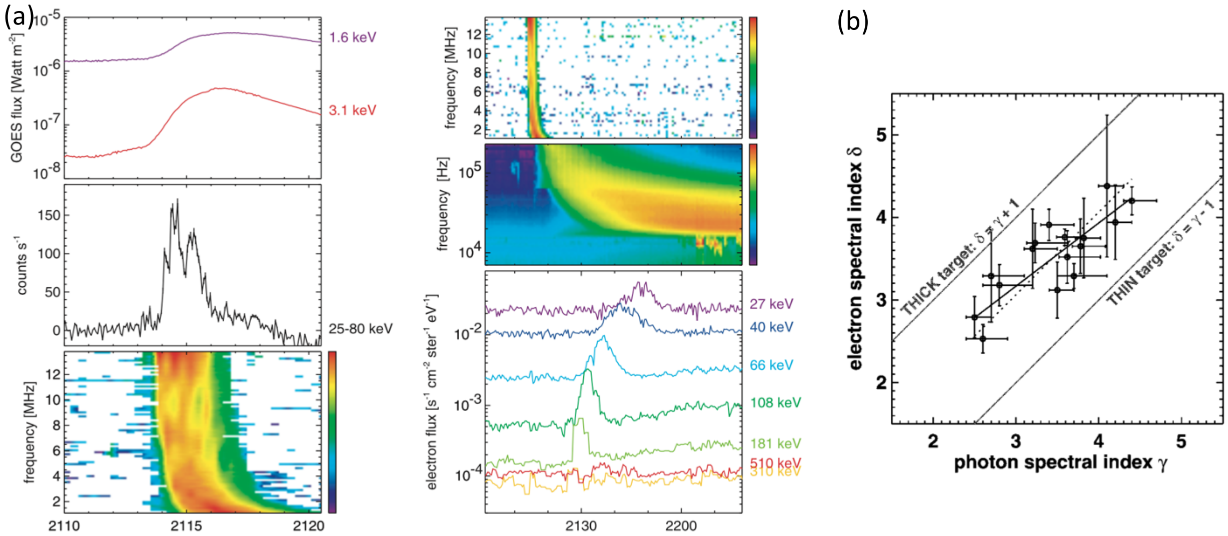

Figure 1: *Taken from Krucker et al. (2007). (a) X-ray, radio and in-situ observations of electrons at 1 au during a solar flare. (b) For prompt events where the inferred release time coincides with the flare HXR burst, there was a correlation between the spectral index of flare-accelerated electrons at the Sun and 1 au, but it did not fit into the simple picture of flare-accelerated electrons produced in either a thin or thick target flaring plasma.*

2. why was the relationship between the HXR producing and the escaping electrons not consistent with a simple CTT scenario? and 3. why was the ratio of escaping to HXR-emitting electrons very small? Recently, yet to be published work by B. Alcock et al. reproduced the electron delays at Earth by including distance-dependent and energy-dependent transport effects, finding that the arrival for higher energy electrons (>40 keV) matched well with observation. However, they found that lower energy observations, which predict much more impulsive events at Earth than those observed, could not be reproduced. Late arrival at Earth can be due to delayed transport, or else to late particle release combined with a complex magnetic connection (Klein et al. 2005). Such results can only be further explored by more detailed observational analyses and advanced kinetic modelling. We will build a model that calculates X-ray spectra at the Sun and in-situ electron spectra at 1 au, while considering varying properties of an acceleration region and various realistic transport effects both at the Sun and in the heliosphere (Fig. 2). Subsequently, we will use the vast experience in radio observations within the team to include radio plasma emissions in the high corona that can be compared with ground and space-based radio observations. The inclusion of radio observations will act to further constrain the acceleration region and transport effects (e.g., Kontar & Reid 2009) by including the properties of electrons at intermediate locations between the Sun (X-rays) and the Earth (in-situ; Fig. 2).

ii. In situations where a connection exists, can sunward and earthward electrons be used together to constrain the unknown properties of the flare acceleration region and the interplanetary transport conditions?

To date, the properties of the solar flare acceleration region are poorly constrained by remote X-ray observations alone. Recent observational studies with RHESSI, such as Jeffrey et al. (2015) have shown the existence of strong vertical gradients in the temperature and number density of the flaring corona. The varying spatial and temporal properties of the acceleration region will control if and where electrons are accelerated. Hence, we will examine how such properties contribute to their escape and their observed properties at the Sun and at 1 au. We aim to model extended acceleration regions of varying size, number density, temperature and turbulence levels. The two electron transport models (1. sunward and 2. earthward, see Fig. 2) will be coupled to the modelled acceleration region simultaneously. We will investigate how much influence the properties of our acceleration region have in determining the final observed electron properties, as compared to effects due to the propagation of electrons in both the dense and collisional solar atmosphere and non-collisional interplanetary space. The formation of so-called kappa distributions (Bian et al. 2014), a result of competing

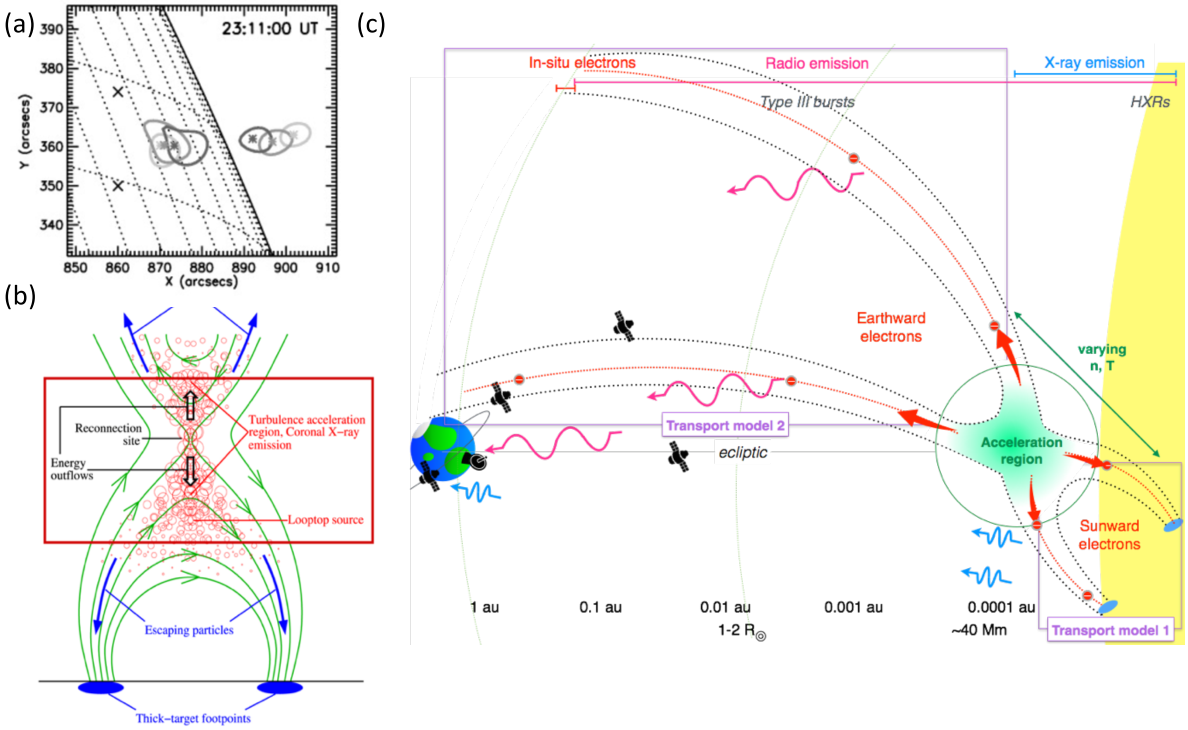

Figure 2: (a) Sui & Holman (2003) - the locations of flare loop top and above the loop top X-ray sources suggest an extended region of particle acceleration and heating with varying properties, (b) Petrosian (2012) – cartoon of the flare acceleration region showing an extended region of varying turbulence where both sunward and earthward electrons are produced. (c) An extension of (a) and (b). Our modelled acceleration region will feed the sunward and interplanetary transport models simultaneously, producing multiple outputs that can be compared with X-ray, radio and in-situ observations at 1 au, and future X-ray and in-situ measurements at different heliospheric locations (down to 0.04 au with the upcoming 2018 Parker Solar Probe mission).

collisional and non-collisional processes can directly be addressed within our modelling framework. A recently extended study of partially occulted flares near the solar limb (Effenberger et al. 2017) will provide a basis of events to constrain the coronal acceleration region properties further. The work will provide analysis capabilities for future X-ray missions such as FOXSI (Christe et al. 2017), a NASA direct X-ray imager with a high dynamic range and better sensitivity for measuring sources closer to primary acceleration regions, even for on-disk flares.

iii. Develop a set of flexible stochastic models that can be used together to constrain different solar flare properties.

After the prime goals (i) and (ii) of the project have been completed, we will have two transport codes (Fig. 2) that feed from a common acceleration region input. These codes will be used by team members for different projects, together or individually. The model will also be ready for comparison with data from future missions: Solar Orbiter (SO, Mueller et al. 2013, launch 2019) and the Parker Solar Probe (PSP, Fox et al. 2016, launch 2018) which will observe flare X-rays (SO) and electrons in-situ (SO, PSP) at distances down to 0.04 au (PSP) from the Sun, and out of the ecliptic (SO).

3. Project timeliness

The investigations and model development proposed here are timely due to the recent progress in the application of stochastic modelling approaches and simulation tools to describe and simulate energetic particle acceleration and transport. This project will focus on solar flare energetic electrons, due to their comprehensive multi-instrument in-situ and remote coverage. Furthermore, we will lay the groundwork for extending the developed models to shock acceleration, and hence the important connection between coronal mass ejections (CME) and SEPs. In a similar way, our project results will inform future studies of accelerated ions. Further, our SDE approach will also allow for studies where the stochastic process can be generalised to study deviations from Gaussian diffusion behaviour which could play an important role in acceleration and transport effects. We will thus prepare important

numerical tools and analysis capabilities for the next generation of inner heliospheric datasets as discussed (Solar Orbiter, Parker Solar Probe). Vitally, our team will build upon, continue the efforts of, and include team members from successful ISSI teams that also studied the propagation of solar flare electrons, such as:
http://www.issibern.ch/teams/electronflare/ and http://www.issibern.ch/teams/energyparticle/

4. Expected output

Initially, our team discussions will form the basis of the kinetic modelling that will produce synthetic X-ray spectra and electron in-situ data that can be directly compared with multiple observations from the last 15 years e.g., RHESSI X-ray, STEREO/SEPT (Müller-Mellin et al. 2008) and Wind/3DP electron data. Imaging and spectroscopy data from SDO/AIA (Lemen et al. 2012) and Hinode EIS (Culhane et al. 2007) will help to determine the properties of the acceleration region alongside RHESSI imaging and spectroscopy. The first expected output will be the results of goals (i) and (ii). Addressing these goals is the prime objective of our team. The development of these simulations is likely to lead to several individual projects that concentrate on more focused properties of flares and their observables (goal (iii)). Hence, we envisage the submission of several refereed papers directly related to the newly developed models, with additional publications from applied topics where team members utilize our newly developed capabilities.

5. Added value of ISSI

This project requires collaboration of researchers working on a broad range of solar and heliospheric research topics with observational, theoretical and modelling expertise. Gathering a research team with such vast experience cannot be easily performed, since researchers from different countries and scientific backgrounds need to be involved. Our cross-disciplinary modelling project requires the input of different researchers experienced in the observational and theoretical studies of:

1. The acceleration and transport of electrons at the Sun (X-rays, collisional transport, hot plasma, turbulent EUV diagnostics)
2. The transport of electrons high in the corona (radio emission processes, non-collisional transport and pitch-angle scattering)
3. The transport of electrons to 1 au (interplanetary transport to 1 au, turbulent scattering, multi-spacecraft observations).

Forming an ISSI team provides the best opportunity for performing collaboration with such a vast range of expertise. The pulling of such experience required for the project cannot be easily performed in other situations, since the usual specialized meetings do not allow a sustained interaction of researchers with a broad range of expertise from different scientific communities. The first meeting will be used to discuss the basic outline of the model, select candidate events suitable for case study (this is a task we might tackle before the first meeting via e-mail and teleconferences), include presentations and discussion regarding the plasma properties and required transport effects to be included in each part of the model and how this will be achieved. The second meeting will be used to present and discuss the preliminary model outputs and conclusions and their similarities and differences to observations, as well as how to best proceed with future modelling and observational studies, including novel future instrumentation. Between meetings, we hope to organize sessions at conferences and workshops, have frequent teleconferences to discuss our progress and maintain small group collaborations between different team members.

6. Schedule, facilities and financial support

The first meeting will be in Winter/Spring 2019 and the second meeting will follow during 2019 or early 2020. Our team will require meeting rooms, projection facilities, white boards, wired and wireless Internet connections, facilities for teleconferences using Skype, and electrical adaptors. Each team member will require a per diem for living expenses while residing in Bern. The team leader will require additional support for travel from Glasgow, UK.

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A2 Acronyms

keV, MeV – kilo electronvolt, mega electronvolt; **au** – Astronomical Unit; **HXR** – Hard X-ray; **SEP** – Solar Energetic Particle; **SEE** – Solar Energetic Electron, **RHESSI** – Ramaty High Energy Solar Spectroscopic Imager; **Wind/3DP** – Wind 3D Plasma and Energetic Particle; **FOXSI** – Focusing Optics X-ray Solar Imager; **STEREO/SEPT** – Solar Terrestrial Relations Observatory Solar Electron and Proton Telescope; **SDO/AIA** – Solar Dynamics Observatory Atmospheric Imaging Assembly; **Hinode/EIS** – Hinode Extreme Ultraviolet Imaging Spectrometer; **SDE** – Stochastic Differential Equation.