Institution: University College London

Unit of Assessment: 9 – Physics

Title of case study: Increasing public understanding of solar physics

Period when the underpinning research was undertaken: 2009-2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Lucie Green	Professor of Physics	2005 - present

Period when the claimed impact occurred: 2014 – 2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact (indicative maximum 100 words)

UCL's research into the characteristics of the coronal mass ejections of the Sun has stimulated public interest in space weather through a large number of engagement activities. Since 2013, public and schools talks related to research conducted by Professor Green have resulted in attendees having increased knowledge and being inspired to study physics. UCL's ongoing engagement with the Met Office has transformed the organisation to be a global influencer in space weather. UCL's solar research, featured in Science Museum exhibitions, poetry and books, has reached an audience of hundreds of thousands, worldwide and increased people's understanding and appreciation of astrophysics.

2. Underpinning research (indicative maximum 500 words)

Professor Green at UCL conducted research into the evolution of the Sun's atmospheric magnetic field and the origin of vast magnetised plasma eruptions known as coronal mass ejections. The work built on previous foundational studies by the same author that showed the progenitor of coronal mass ejections to be a specific twisted magnetic field configuration. The latest findings reveal the characteristics of these twisted "flux ropes" and the mechanisms by which they form. Taken together, the research shows that flux ropes are much more common in the solar atmosphere than previously thought (**R1-R6**).

The work has shown the importance of different types of photospheric flows that lead to specific magnetic flux rope configurations. Work led by Green showed that reconnection in the photosphere/chromosphere driven by supergranular flows (**R1, R2**) forms a magnetic flux rope that is of a bald patch separatric surface (BPS) type, whereas work carried out by Green's PhD student Alex James showed that reconnection occurring in the corona, driven by orbiting motions of magnetic fragments in the photosphere, forms ropes of a hyperbolic flux tube (HFT)-type (**R4, R5**). Knowing the specific configuration of the flux rope is important since it affects the stability of the structure and its likelihood of eruption. For example, a BPS flux rope – with its underside rooted in the dense lower atmosphere – may need to undergo further evolution before an eruption is possible. A HFT, on the other hand, can collapse into a current sheet if perturbed, allowing flare reconnection to take place to drive a coronal mass ejection. In addition, the shape/height of the rope play are important factors in the likely occurrence of an ideal instability. Work led by Green (**R2**) and work led by a PhD student in the US (Savcheva) with strong guidance from Green (**R3**) revealed that flux ropes can transition between BPS and HFT types in the time period before their eruption.

When flux ropes are ejected from the Sun as a coronal mass ejection (CME), they can propagate to the Earth and disturb the geomagnetic field, leading to a chain reaction of processes that ultimately results in disruption to modern technologies such as power distribution, communications and navigation services. This area of research that looks at how the Sun affects the Earth is known as space weather. Part of what influences the geo-effectiveness of the flux rope is down to its orientation and the details of its configuration when interacting with the Earth's magnetic field. An analysis of whether observations of flux ropes on the Sun (just before they erupt) can be used to forecast their orientation at Earth, and therefore their likely space weather impact, was led by a PhD student in Finland (Palmerio) under supervision from Green. The work (**R6**) showed the approach to be promising and highlighted the future research direction needed.

3. References to the research (indicative maximum of six references)

R1. **Green LM**, Kliem B. (2009) Flux rope formation preceding coronal mass ejection onset *Astrophysical Journal Letters,* 700, L83. doi:10.1088/0004-637X/700/2/L83
R2. **Green LM**, Kliem B, Wallace AJ. (2011) Photospheric Flux Cancellation and Associated Flux Rope Formation and Eruption. *Astronomy and Astrophysics*, 526. doi:10.1051/0004-6361/201015146
R3. Savcheva AA, **Green LM**, van Ballegooijen AA, DeLuca EE. (2012) Photospheric Flux Cancellation and the Build-up of Sigmoidal Flux Ropes on the Sun *Astrophysical Journal*, 759, 105. doi:10.1088/0004-637X/759/2/105
R4. James AW, **Green LM**, Palmerio E, Valori G, Reid HAS, Baker D, Brooks DH, van Driel-Gesztelyi L, Kilpua EKJ. (2017) On-Disc Observations of Flux Rope Formation Prior to Its Eruption. *Solar Physics*, 292, 24. doi:10.1007/s11207-017-1093-4
R5. James AW, Valori G, **Green LM**, Yang L, Cheung MCM, Guo Y, van Driel-Gesztelyi L. (2018) An Observationally-Constrained Model of a Flux Rope that Formed in the Solar Corona. *Astrophysical Journal*, 855, 16. doi:10.3847/2041-8213/aab15d
R6. Palmerio E, Kilpua EKJ, James AW, **Green LM**, Pomoell J, Isavnin A, Valori G. (2017) Determining the Intrinsic CME Flux Rope Type Using Remote-sensing Solar Disk Observations. *Solar Physics*, 292, 39. doi:10.1007/s11207-017-1063-x

4. Details of the impact (indicative maximum 750 words)

The Sun plays a central role in all our lives, from the more apparent provision of heat and light to the much less well-appreciated impact it has on our modern technological systems. The phrase “space weather” is now used to describe changes in the near-Earth space environment, driven by the Sun’s activity, that lead to these technological impacts. Through her public engagement programme, Green’s research has increased awareness and knowledge of space weather and solar physics across a range of audiences including schoolchildren, the public and other stakeholders, such as the Met Office.

Increased understanding of solar physics among school children

Green effectively shared her research on coronal mass ejections (CME) with more than 90,000 people (students aged 5-18 and science teachers) at more than 45 face-to-face school events in the UK from 2014 to 2020. Fifteen of these outreach events had over 1,600 GCSE students in attendance. Topics discussed during these engagement activities raised understanding of solar physics research findings and stimulated interest among students and teachers, as demonstrated by the feedback given by audience members. The Co-Principal in one of the secondary schools acknowledged that through the lectures the students’ knowledge of solar physics had broadened beyond the national curriculum (**S1**). The lectures inspired both students and teachers, and led to establishing a new after school club “Intro to Astrophysics”. In their feedback, students commented that “Prof Green made complex physics seem accessible” (**S1**). One of the teachers found the presentation by Green “fascinating and enjoyable by all, she had the ability to make a hard topic easy to understand by all”, and said “I found the talk about magnetic flux ropes by Professor Lucie Green the most interesting and useful because I didn't previously know how CME's worked or what caused them” (**S2**).

Inspiring female students to pursue studies and a career in STEM

Green’s public engagement activities had a significant influence on female students by increasing their understanding of solar physics and changing their perception about becoming a physicist. After “Star Gazing Party”- STEM Festival Week in 2019, a teacher commented: “Our Year 10 female students had mentioned that it was wonderful to see such a successful female scientist” (**S1**). This style of engagement event led by Green inspired females to pursue studies and a career in physics and contributed to an increase of 11% (from 21% in 2012/2013 to 32% in 2019/2020) female student intake to physics at UCL during the current impact period. In addition, the female entries to physics course at UCL were 9% higher compared to the national level (23%) of female entries to university physics courses in 2019/2020. One of the female students acknowledged how Green’s talk increased her awareness and ignited her interest in physics: “I attended a GCSE science live talk you gave a few years ago where hearing your passion for solar physics started my interest in physics. Your talk (on solar physics) really allowed me to imagine myself as a woman in physics and also gave me the idea to do solar physics for this project”. A current female PhD student in solar science commented that Green’s talk increased both her interest in physics and her confidence to pursue her studies: "I was struggling with AS physics and debating whether to drop it after AS level (only a few women in the class, didn't feel clever enough etc.) but after your talk I decided to carry it on to A level which I really enjoyed!" (**S2**).

Increased understanding of solar physics among the public

Green discussed her research during 85 events for adult learners or family audiences carried out between 2013 and 2020. Direct engagement included talks at science festivals (Cheltenham Science Festival, Astrofest, New Scientist Live, and the Winchester Science Festival), literature festivals (Fairford Festival of Fiction, Harrogate Festival, and Hay Festival), science centres, poetry evenings and arts events. Audiences expressed appreciation for Green's talks on solar physics, as evidenced by the comment "Thanks again to @Dr_Lucie for a fascinating and fun talk last night about the Sun. Flux tubes are a fascinating subject!" (**S3**). Recognition of Green's excellence in communicating her research with school children and the public led to the award of the Lise Meitner Medal and Prize from the Institute of Physics in 2017.

Research-inspired exhibition

Within the UK physics community, Green's expertise in solar physics made her a natural choice to become the first astrophysicist on the advisory board of the Science Museum in 2012. In her position as a board member, Green has contributed to the strategic direction of the museum's cultural offer by embedding knowledge of cutting-edge solar physics, and space science as a whole (**R1-R6**), in the institution. The Science Director commented: "After series of discussions with senior staff at the Science Museum and other board members about the current developments in astrophysics and space science, notably research related to solar storms, Professor Green **inspired one of our blockbuster exhibitions** - The Sun: Living with Our Star. Professor Green became a member of the exhibition committee and **her expertise and knowledge about solar physics were invaluable in the process of curation and the success of this exhibition**" (**S4**).

The exhibition was open to visitors from 6th October 2018 to 6th May 2019 at the Science Museum in London and from 18th July 2019 to 5th January 2020 at the Science and Industry Museum in Manchester. During this time, 69,000 visitors viewed and engaged with it. In their feedback, visitors appreciated how the exhibition helped them to understand a variety of topics related to the impact of the Sun on our lives through space weather: "it [the exhibition] looks at future problems caused by the sun, namely solar storms, and there was an excellent quiz for everyone **to learn about what we would need in the case of a solar storm**", "enjoyed an interactive display on surviving a solar storm where visitors guess what they might need the most to cope" (**S5**). Moreover, the exhibition was featured in 78 dedicated articles (including the Guardian, New Scientist, The Evening Standard and Time Out), 2,270 exhibition mentions and 41,989 tweets (**S4**).

Research-inspired poetry and books

Green worked closely with the poet, who had a one-year residency at UCL Mullard Space Science Laboratory (MSSL) in 2014. This collaboration inspired him to publish his book *Sunspots* (published in 2015 by Penned the Margins). The poetry in the book directly draws upon and discusses Green's research into solar eruptions and magnetic flux tubes. The author acknowledged the influence of the underpinning research on his work: "I was able to add depth and richness to my book Sunspots, which **increased its quality and helped lead to strong sales and a successful tour** of my one-man show based on the book" (**S6**). The poems in *Sunspots* gave readers a new perspective and understanding of solar physics, evidenced by reviews: "His [the poet's] knowledge of Sun-science comes through in his application of scientific concepts and language, and his poems reveal the nature of the Sun via its interaction with us and with the broader universe", "The whole concept is fascinated and faced with both poetical and scientific expertise" (**S7**).

In 2016, Green published her own popular science book *15 Million Degrees: A Journey to the Centre of the Sun* that has been translated into Dutch, German, Italian, and Chinese, and has sold 12,000 copies in the UK alone (**S8**). The book provides readers with an overview of solar physics over the centuries and discusses her research (**R1**, **R2**, **R3**). Readers recognised that this book **changed their understanding of solar physics, as evidenced by the reader comment:** "[the book] explained some key concepts that I had struggled to get my head around for many years" (**S8**). In addition, readers confirmed that the book **increased their knowledge and awareness**: "It [the book] was written so that a non-academic like myself could understand. I never realized how amazing and dynamic our Sun is. And how integral magnetic fields are to everything" (**S8**).

Influencing organisational change and knowledge of space weather forecasters

The underpinning research (**R1-R6**) has been translated into training for space weather forecasters and stakeholders from across the space weather sector. For example, Green led training sessions on her solar physics research at the Flarecast workshop in 2017 (30 attendees), the European Space Weather Week in 2014 (350 attendees) and training schools for forecasters at the Met Office Space Weather Operations Centre (MOSWOC) in 2017 and 2018 (8 attendees). The longitudinal

engagement with MOSWOC contributed to changes in the organisational culture. The Senior Operational Meteorologist and Lead Space Weather Adviser at MOSWOC commented: "The Science of Space Weather training programme (…) provides our forecasters with a better understanding of the science of space weather (…). **In the last seven years the Met Office has transitioned from an organisation not involved in space weather to becoming genuinely influential globally in this important field. Our collaboration with UCL has helped that transition immeasurably**" (**S9**). Currently, MOSWOC relies heavily on the use of images of the Sun and their interpretation to forecast space weather related to events such as CMEs. Hence, the underpinning research that was communicated at the training events increased forecasters' knowledge and the competences required for their role, as evidenced by comments: "Information on sigmoids was great for helping understand how flares work" and "A useful in-depth understanding of magnetic reconnection and flux rope emergence" (**S10**).

In 2018, Green raised awareness of the impact of space weather by giving talks to 50 policymakers in the Department for Business, Energy & Industrial Strategy (BEIS) Science & Engineering Network (SEN) and to the Department for Exiting the EU (DExEU), both discussing research in (**R1-R5**). The feedback evidenced increased knowledge among policymakers: "it (…) certainly taught me more about coronal mass ejections than I ever knew before!" (**S10**).

5. Sources to corroborate the impact (indicative maximum of 10 references)

S1. Supporting letter from Co-Principal at the UCL Academy (06/11/2020) corroborate statements provided.
S2. Colligated testimonies from a secondary school and university student corroborate statements provided.
S3. Commentary provided by an attendee of 'Our Brilliant Sun' with Professor Lucie Green at the Brighton Cafe Scientifique (02/11/2019) corroborate statement provided.
S4. Supporting letter from the Science Director at the Science Museum Group corroborate statement provided and media coverage of the exhibition *The Sun: Living with Our Star*.
S5. Reviews of 'The Sun: Living with Our Star' exhibition published on personal blogs (08/10/2018 and on 13/03/2019) corroborate statements provided.
S6. Supporting letter from the poet (27/01/2020) corroborate statement provided.
S7. Reviews and commentaries on 'Sunspots' published on Magma Poetry blog (date not provided) and Goodreads (08/01/2017) website corroborate statement provided.
S8. Data on the *15 Million Degrees: A Journey to the Centre of the Sun* book sales and readers reviews corroborate number of book copies sold in the UK and statements provided, respectively.
S9. Blog post discussing the training programme for space weather forecasters at the Met Office Space Weather Operations Centre (21/08/2018) corroborates statement provided.
S10. Supporting statements from training courses participants at MOSWOC and BEIS (13/07/2018) corroborate statements provided.

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