Institution: University College London (UCL)

Unit of Assessment: 9 – Physics

Title of case study: Stimulating public engagement with solar physics

1. Summary of the impact

UCL's discoveries of the existence of magnetic flux ropes in the solar atmosphere and their link to sunquake generation have stimulated public interest in science and led to a large volume of engagement activities. Since 2008, there has been a high demand for public and schools talks related to research conducted by staff within the Department of Space and Climate Physics – also known as the Mullard Space Science Laboratory (MSSL) – with attendees being inspired and gaining increased knowledge. Teaching resources and talks at teacher training events have enabled teachers to include MSSL research in inspirational science lessons. Sustained and on-going relationships have been developed with local schools, adult education groups, the media and the local community; for example, at the 2009 MSSL open day visitors from the local area benefited from raised awareness and improved knowledge about space science.

2. Underpinning research

During the period 2005-13, members of staff within UCL's MSSL conducted research into the magnetic configuration of eruptions from the solar atmosphere (known as coronal mass ejections) and the origin of transient seismic activity on the Sun (known as sunquakes).

A combined experimental and theoretical study of the magnetic configuration of coronal mass ejections (CMEs) was conducted from 2005 onwards by MSSL's Lucie Green (Royal Society Dorothy Hodgkin Research Fellow 2005-2010; Leverhulme Research Fellow 2010-2012; Royal Society University Research Fellow 2012-present) and Bernhard Kleim (PDRA 2008-2012). The experimental data used in this research, acquired by internationally funded and operated space telescopes that have major UK hardware contributions, were measurements of the magnetic field at the visible surface of the Sun and observations of the magnetic field configurations in the solar atmosphere as revealed by plasma emission in the X-ray and extreme ultraviolet wavelength ranges. The magnetic configuration of CMEs was determined by using these data in combination with the latest theoretical approaches to modelling magnetic configurations in the solar atmosphere. This approach led to the first unambiguous determination of the magnetic configuration of a CME at the point of eruption and showed it to be a bundle of twisted magnetic fields known as a flux rope [1], answering one of the most outstanding problems in solar physics. The results provided a clear observational signature to identify flux ropes that exist low in the solar atmosphere and showed the mechanism by which flux ropes form before their eruption as a CME. The observations were then used to calculate the magnetic flux content of the ropes [2], another question of fundamental importance in CME and space weather research. MSSL's observational identification and measurements of the flux content of the ropes were then compared with models of magnetic flux ropes created at the Harvard-Smithsonian Center for Astrophysics [3], with the finding that these models provided support for the observational work.

From 2009, Sergei Zharkov (PDRA 2009-2012) and Sarah Matthews (Lecturer 1999-present) conducted research that built on these results by analysing and modelling the Sun's seismic activity. Over the last decade, it has become well established that beams of particles accelerated during a solar flare can travel into the Sun, delivering a significant momentum pulse from the solar atmosphere into the solar interior and producing a sunquake. The MSSL work led to the discovery that sunquakes can also be triggered during the eruption of flux ropes [4]; the research showed that as a magnetic flux rope accelerates away from the Sun, the rapidly changing magnetic field anchored in the solar surface may deliver the required momentum pulse. These results highlight the possibility of a different, but important, role of the magnetic field not previously considered in the triggering of sunquakes, which provides an excellent opportunity to probe the physical processes involved in this transport of momentum.

3. References to the research

[1] Flux rope formation preceding coronal mass ejection onset, L. M. Green and B. Kliem, *Astrophysical Journal Letters*, 700, L83 (2009) doi:10/dwqnch

[2] Photospheric flux cancellation and associated flux rope formation and eruption, L. M. Green, B. Kliem and A. J. Wallace, *Astronomy and Astrophysics*, 526, 2 (2011) doi:10/fccz92

[3] Photospheric flux cancellation and the build-up of sigmoidal flux ropes on the Sun, A. A. Savcheva, L. M. Green, A. A. van Ballegooijen and E. E. DeLuca, *The Astrophysical Journal*, 759, 105 (2012) doi:10/pvp

[4] 2011 February 15: Sunquakes produced by flux rope eruption, S. Zharkov, L. M. Green, S. A. Matthews and S. S. Zharkova, *Astrophysical Journal Letters*, 741, L35 (2011) doi:10/d4j2tr

References [1], [2] and [3] best indicate the quality of the underpinning research.

4. Details of the impact

MSSL research findings have led to a high level of public interest and demand for public engagement activities related to the specific research described in section 2. Within the REF impact period, MSSL researchers have been invited to speak at numerous public and school events and have received a large volume of requests for media interviews and other media engagement activities.

Schools talks: Seventy talks were delivered by Green to over 20,000 school students between 1 January 2008 and 31 July 2013. Audiences ranged in size from 30 to 1,500 people and included both primary and secondary school students. The talks covered a range of research that was conducted at MSSL, including an overview of the research in references [1] and [4] above. On-going relationships were formed with a number of schools in the south of England; for example, St. Teresa's school in Effingham, Surrey, and Thomas Hardye School in Dorchester, Dorset. Both of these schools have benefited from repeat visits from Green and other researchers and engineers at MSSL. As well as talks given in the schools, MSSL also hosted visits from school groups and delivered talks at the laboratory itself. A selection of feedback [A] demonstrates that the talks have inspired students, stimulated their interest in science, and improved their knowledge and understanding of the topics:

"Years 5 and 6 were hugely inspired by a presentation at St Teresa's from Dr Lucie Green, which provided an excellent start to our National Science Week activities. They found her talk on the Sun, Solar System and other stars absolutely fascinating, prompting them to ask plenty of questions. […] Our Year 5 groups have been visiting Lucie at the Mullard Laboratory for several years now. This is a popular and highly valuable trip, which supports the girls' science studies on the Earth, Sun and Moon physics topic. We appreciate this exciting link with the scientists at Mullard and are incredibly grateful for its significant contribution to the education of our girls."

"The students (and staff!) at The Thomas Hardye School in Dorset have been very fortunate to benefit from several high-quality enrichment opportunities presented by scientists and engineers from the Mullard Space Science Laboratory since 2008. Year 9 and Year 10 students were able to quiz Dr Lucie Green at a "Meet the Scientists" event […] As a result, students have found their pre-conceptions about scientist […] stereotypes altered in a positive way. […] Dr Green returned in February 2013 to impress a packed audience of more than 500 people drawn from the community and school with "Solar Max". The numbers of THS students taking science (especially physics) […] beyond school have increased steadily over the intervening years - the impact of meeting cutting-edge inspirational scientists […] who have a passion for their subject is invaluable in helping the school make students aware of cross-curricular STEM subjects and the myriad of career possibilities that they offer."

Science education: From 2008 onwards, MSSL's Green developed a series of teaching resources [B] to aid delivery of the primary and secondary school science curricula by teachers. These resources, which are underpinned by Green's research and experience at MSSL, provide practical ideas for bringing Solar System science into the classroom and enable teachers to illustrate their teaching with examples from current research. They were one of the top 25 resources downloaded through the ESERO (European Space Education Resource Office) section of the National STEM Centre eLibrary website in the 2012 autumn term [B], and continue to be amongst the website's 'Most Popular' resources [C]. Teachers have found the resources to be very effective, with feedback from one reviewer on the website including: "The Sunspots activity worked excellently with my year 9 GCSE Astronomy class. It is a straightforward task that produces a clear result and

by combining the information from the graphs it is clear there is a pattern to the sunspot cycle but variation in this pattern. It was very good for showing the advantages of displaying data in graphs rather than tables and for building up graphs skills, which is something I'm always surprised at the number of students who struggle with it." [C]

Green also delivered talks during the REF impact period to a total of around 300 school teachers at continuing professional development (CPD) events. These talks covered the basics of the Sun and observing the Sun from space using missions for which MSSL has supplied instrumentation, as well as the research findings in references [1-4] above. Activities included delivering the Association for Science Education keynote John Lewis lecture in January 2012, delivering the Institute of Physics (IoP) keynote lecture in July 2012, speaking at the ESERO Space Education Day of the UK Space Conference in July 2011, and speaking at the Prince's Teaching Institute in March 2010. Her input enabled the teachers to take current MSSL research (that in references [1], [2] and [4] above) into the classroom and to develop new lesson plans. Feedback collated in the evaluation of the IoP keynote lecture included: "The keynote speaker was fantastic – I have a lesson in mind for year 7s who are very interested in the solar system" and "Fantastic start with such enthusiasm – info on sun was excellent, possibly best ever!" [D]

The ESERO Space Education Day was attended by 25 primary school teachers and 69 secondary school teachers from across Britain. Evaluation of the day as a whole found that teachers "were overwhelmingly positive about their experiences of attending the event" [E], and that the event was valuable as it connected teachers with expert speakers who provided information about current developments in space science together with ways to use this information in the classroom [E].

Public talks: Over 60 public talks were given on MSSL research (references [1-4] above) during the REF impact period, including repeat visits made to adult education societies, astronomical societies and the Cheltenham Science Festival (2010-13). Other events included Astrofest in February 2012 and a public UCL Lunch Hour Lecture, delivered by Green in November 2011 about her research (references [1], [2] and [4] above). The total audience reached through these events is many thousands and is composed mainly of adult and family audiences; for example, Astrofest was attended mainly by adults and had an audience size of one thousand, and the Lunch Hour Lecture had an audience of over one thousand (direct and online webcast).

Public talks delivered by MSSL researchers have also resulted in on-going and sustained relationships with the local community. Feedback from the audience after a community talk about solar physics given by Green at Thomas Hardye School in February 2013 indicated that public interest had been stimulated and understanding of the topic had been increased, and included the following comment: "The fascinating insight into your work was portrayed in such an illuminating manner (apologies for the pun) that even a layman like myself could feel a degree of understanding (well, at least for the basics!), and your enthusiasm is infectious - I seem to be developing a curious fondness for solar magnetic flux ropes, of all things!" [F]

In addition to attending MSSL's public talks, members of the local community visit the department on open days. The 2009 open day was attended by 220 people from the local area. Evaluation of the event showed that visitors "had had their awareness of the space science that occurs locally raised" [G], and that 53% and 27% of visitors rated their learning about space science and the work at MSSL as 'very high' and 'a lot' respectively. Their overall enjoyment of the day was rated as 'very high' by 83% of visitors [G].

Online content: A video discussing Green's research area, and the upcoming solar space missions that she is involved with, was recorded in collaboration with the UK's Astronomy Now magazine in April 2011. This video received over 1,700 views on YouTube between April 2011 and 31 July 2013 [H]. Green also discusses her research on her personal website, which was visited by 30,000 unique visitors during the last three years (up to 31 July 2013). Most visitors were from Europe, with a smaller percentage from North America, South America, Africa and Japan. The number of unique visitors has increased year on year: there were 2,675 in 2010, 8,578 in 2011, 12,110 in 2012, and 6,677 in the first seven months of 2013 [I]. This increase in online visitors demonstrates an increase in public interest in Green's work.

Media activities: The various public engagement activities mentioned above stimulated interest among the media, which has led to increased demand for expert comment from Green on solar

physics research and its relation to space weather and Solar System physics, in addition to on-going relationships with journalists and producers. For example, Green presented a BBC Radio 4 programme on space weather (Solar Max, broadcast April 2013) and has given expert comment in many interviews regarding solar activity and space weather.

Insurance industry: MSSL research (references [1-3] above) has been disseminated to the insurance industry and to the growing UK space weather community; for example, Green visited the Met Office in July 2011 to discuss her research results and their relevance. The visit involved the small team who were responsible for developing the space weather activity at the Met Office at that time and has led to on-going engagement. Talks discussing flux ropes and their potential for use to predict space weather were also delivered by Green at two events for insurance industry employees: the EQECAT London conference in May 2011 and the IUA (International Underwriting Association) Catastrophe Risk Management Conference in October 2012. This dissemination has led to an increased understanding amongst these communities of how space weather events could affect the insurance industry and of what steps they need to take to minimise the impact on business operations and earnings. Feedback from the IUA event showed that Green's talk was by far the highest rated of the conference (84% of respondents rated it as 'excellent') [J], with the attendees greatly valuing the science and its importance in the emerging risk of space weather. This positive feedback has led to Green being an invited speaker at the IUA's 2013 event and to on-going dialogue with several of the 2012 conference attendees. A further outcome of MSSL's interaction with these communities is a national meeting being held in December 2013 that will bring together MSSL academics with the Met Office, the National Grid and the insurance industry to discuss future collaborations.

While the impacts focus on UCL contributions, they are also underpinned by a wide body of solar physics research that was conducted over many years by research teams in many institutions worldwide. These other institutions therefore share in the credit for the impact generated.

5. Sources to corroborate the impact

[A] Compilation of feedback from attendees of schools talks – corroborates that attendees have been stimulated, interested and engaged. Available on request.

[B] A Teacher Fellow at ESERO can be contacted to corroborate that Green's resources were in the top 25 ESERO downloads in the 2012 autumn term. Contact details provided separately.

[C] The schools resources are available on the National STEM Centre eLibrary website at http://bit.ly/16aaenD. Corroborates that the resources are amongst the website's 'Most Popular' and that they have been useful in schools (see the review on the site for the secondary resources).

[D] Evaluation of the IOP keynote lecture – corroborates that teachers were inspired by the research. Available on request.

[E] Evaluation of the European Space Education Resource Office: Final report, J. Jeffes, S. Straw and E. Lamont (2012) Slough: NFER – corroborates that the ESERO Space Education Day was valuable to teachers (see page 35). Available online: http://bit.ly/18lIElQ.

[F] Feedback from an attendee of an MSSL community talk in February 2013 – corroborates that interest was stimulated and understanding of the topic was increased. Available on request.

[G] Project Evaluation & Learning Form for MSSL community open day 2009 – corroborates that visitors' awareness and knowledge were raised by the event. Available on request.

[H] Astronomy Now video on YouTube: http://youtu.be/AsmtMcTkbtU – corroborates the number of views.

[I] A pdf containing details of website visitor numbers is available on request.

[J] IUA Catastrophe Risk Management Conference Evaluation Form – corroborates the high rating of Green's talk by event attendees. Available on request.