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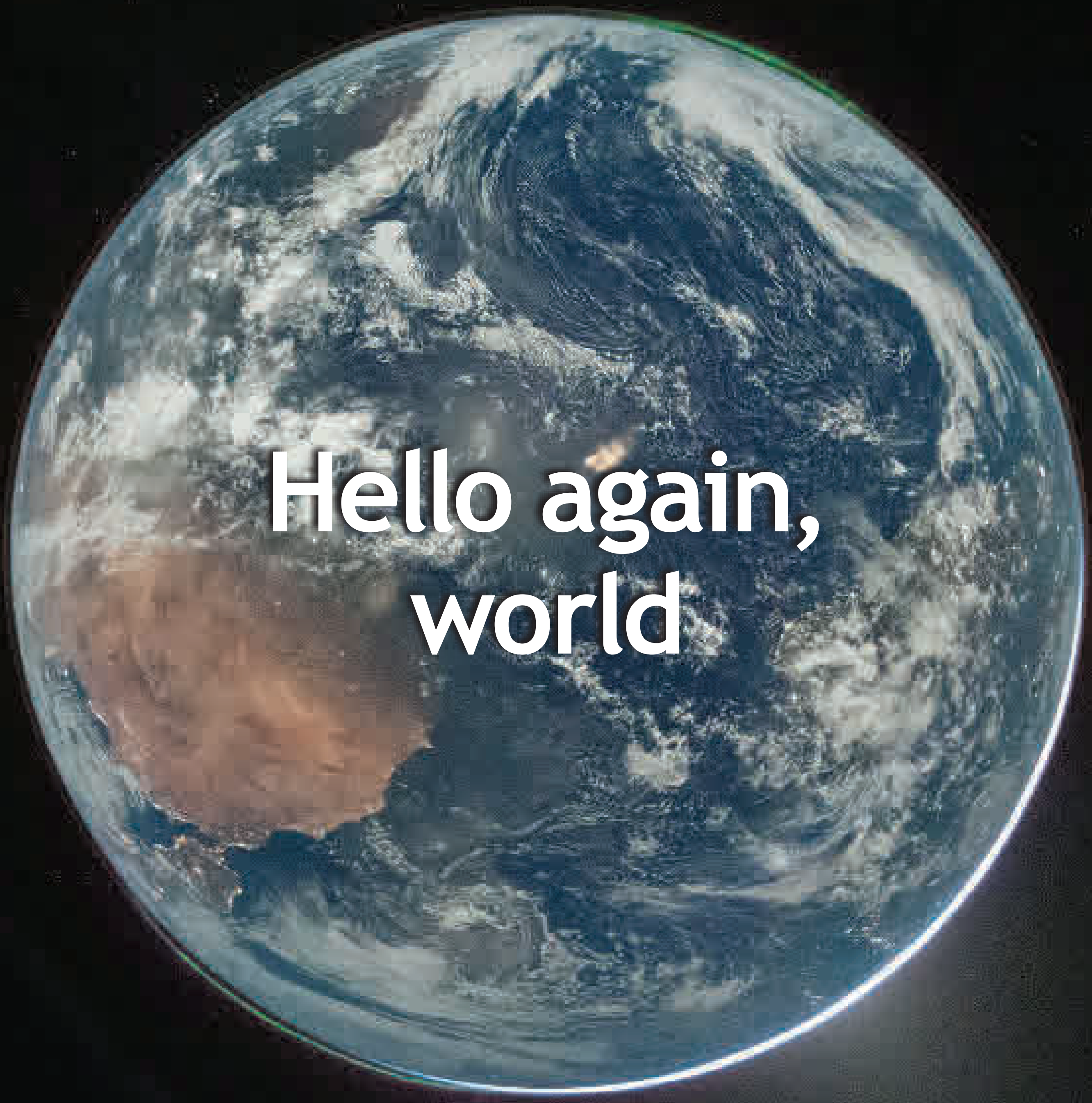
Royal Astronomical Society



Hello again, world

Hottest influencer *How the Sun affects the Earth*

STFC cuts *Funding crisis for UK astronomy*

UKI-Array *Game-changing geophysical instrumentation*

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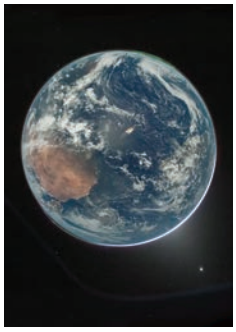

Get in touch

Astronomy & Geophysics publishes news, reviews and comment on topics of interest to astronomers and geophysicists. See academic.oup.com/astrogeo for more details or contact the editor:

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On the cover

This issue we present a number of perspectives on the Earth, but none more iconic than the most ambitious selfie of the century so far, taken by the crew of Artemis II (NASA)

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News

Editorial
Good news, bad news

There's a conundrum within this issue of *A&G* – and it centres on the future of our research.

Within these pages is a vivid snapshot of a thriving community: advancing our understanding of the Sun's influence on Earth; probing planetary environments, from auroral processes across the solar system to the conditions surrounding Mercury; and envisioning ambitious new seismic infrastructure that could transform geophysical research across the UK and Ireland. We also reflect on the legacy of someone whose leadership helped shape modern space science, and hear from the RAS's new president about plans to lead the community forward.

Yet this focus on innovation, ambition and discovery is set against a far more sobering backdrop: reality. The scale of the proposed and actual cuts to STFC funding, outlined in this issue, threatens to strike at the very heart of the enterprise that makes such progress possible. The highest price will be paid by those who should become the future of our community: early-career researchers. Curtailed projects, lost opportunities, and erosion of the expertise and ambition that have long underpinned the UK's leading role in astronomy and geophysics research.

The contrast is stark. Just as our science is delivering unprecedented insight and global collaboration, the resources required to sustain it are under severe strain. The question facing us is not only what discoveries lie ahead, but whether we will retain the capacity to pursue them.

Indra Bains, Sue Bowler
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Caroline Herschel Medal 2026: Heike Rauer

The 2026 Caroline Herschel Medal, a joint UK-German award to an exceptional women astronomer, goes to Prof Dr Heike Rauer of the German Aerospace Center and Freie Universität Berlin. The award recognises her outstanding contributions to exoplanet science – especially her leading role in the ESA mission PLATO – and her exceptional and committed service to the astronomical community, in leadership, in scientific collaborations such as the Next Generation Transit Survey, and in mentoring. The Medal is jointly awarded by the RAS and the German Astronomical Society (Astronomische Gesellschaft); Prof Rauer received her medal in a ceremony at the British Embassy in Berlin. **tinyurl.com/bdfwfezz**

(Royal Astronomical Society)

Shrinking STFC science

Researchers at all levels will find out more about the proposed funding cuts from an STFC Council and Executive Board meeting to be held this month. According to a letter from STFC executive chair Michele Dougherty, the meeting will consider potential scenarios presented by the Particle Physics, Astronomy and Nuclear Physics Science Board, including impact assessments. She thanked the community for their engagement and feedback, which included a Town Hall meeting about the potential impact on astronomy, hosted at Burlington House by the RAS. Further consultation will follow the June meeting, including with UKRI and the Department of Science, Innovation and Technology; international expert review will form part of the process. tinyurl.com/mpr7nbbt

RASReach 2026

Navigating the Science Communication Landscape was the title of an RAS workshop and networking day at the University of Manchester in March, uniting science communicators, educators, researchers, and practitioners. The event created an open space for participants to share experiences, discuss challenges, and explore opportunities within an evolving and uncertain environment.

The event was organised by RAS outreach staff Lucinda Offer and Adam Boal, together with Soheb Mandal and his colleagues from the University of Manchester. Sessions addressed key themes including freelancing and funding, education and outreach, diversity and inclusion, STEAM, and the growing role of AI in engagement practice. Attendees valued the opportunity to engage in honest conversations with peers who understand the complexities of working in science communication today. **tinyurl.com/3x7umpvf**

(RAS/Philip Black)

New Editor-in-Chief for RAS journal

Matt Middleton of the University of Southampton has been appointed Editor-in-Chief of *Monthly Notices of the Royal Astronomical Society*, taking over from David Flower of the University of Durham, who has spent more than a decade in the role. He will be in post at the start of 2027, which marks the journal's bicentenary.

Prof Middleton's research interests lie in accretion onto compact bodies, especially black holes, and in X-ray astronomy, including the ESA observatory NewAthena. He is a former vice-president of the RAS and when on Council took a leading role in the creation of the new journal *RAS Techniques and Instruments*.

"In a rapidly changing world, there has never been a more important time to ensure the quality and integrity of published science," said Prof Middleton. "I am deeply honoured to be able to take the journal into its next chapter, and excited to celebrate its 200th anniversary with the huge community the journal supports."
tinyurl.com/447bmc5m

GJI on ResearchGate

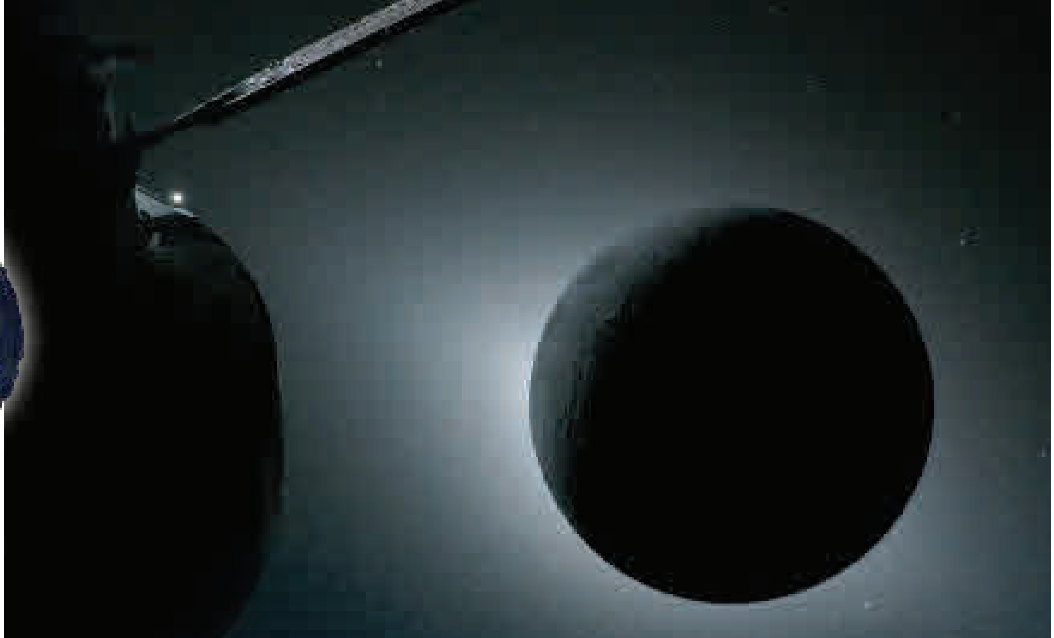
The RAS journal *Geophysical Journal International* is now part of an Oxford University Press (OUP) pilot of ResearchGate's Journal Home (**tinyurl.com/2s3hkfw2**). This pilot will enable users on ResearchGate's platform to read the full text content and interact with journal-level information and metrics on a dedicated journal homepage. Through this pilot the RAS and OUP hope to maximise the reach of the journal, drive additional quality submissions, and better demonstrate the impact of the journal. **tinyurl.com/5n92u4h8**

Modelling Psyche ready for 2029

Psyche, in the main belt between Mars and Jupiter, is the largest known metallic asteroid, at 225km in diameter (shown in an artist's impression).

It might be the core of a layered body remaining after a collision stripped away the rocky mantle, or perhaps a porous mixture of rock and metal left over from a more catastrophic collision. Modelling of an impact crater near the asteroid's north pole suggests an impactor about 5km across is the most likely origin, whatever the internal make-up of the asteroid.

But details of the crater shape may provide more information about its inner structure when NASA's Psyche mission arrives in 2029. A research team led by Namya Baijal (University of Arizona, Tucson) present the results in *The Journal of Geophysical Research: Planets*. **tinyurl.com/muacscp9**
(Maxar/ASU/P.Rubin/NASA/JPL-Caltech)



Back to the Moon

NASA's Artemis II mission returned astronauts to the far side of the Moon in a successful 10-day mission that made headlines around the world. The astronauts (three US, one Canadian) began successfully on the Space Launch System and their Orion capsule – named Integrity – performed well, once they got the innovative $30m toilet working properly. The mission took the crew further from Earth than any others, and tested systems crucial to the continuing Artemis programme. Integrity followed a different re-entry trajectory to that of Artemis I, and did not experience the heat shield degradation that had been a cause for concern. (NASA)

Breaking-up is hard to observe

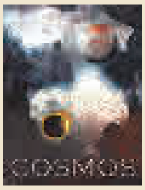
NASA's Hubble Space Telescope (HST) has accidentally caught a comet in the act of breaking apart. Images of C/2025 K1 (ATLAS) were taken just a month after its closest approach to the Sun. Dennis Bodewits (Auburn University) and team estimate the comet began to disintegrate eight days before the HST viewed it. A full report is given in *Icarus*. **tinyurl.com/35kh287y**
(Image: NASA, ESA, Dennis Bodewits (AU); Image Processing: Joseph DePasquale (STScI))

Iron-poor, carbon-rich relic

Researchers have discovered one of the most chemically primitive stars ever identified. PicII-503 resides in the tiny ultra-faint dwarf galaxy Pictor II. Anirudh Chiti (Stanford University) and colleagues suggest this is a second-generation star that preserves the abundances in low-energy supernovae of first-generation stars. It has 40000 times less iron than the Sun, but far more carbon. The study appears in *Nature Astronomy.* **tinyurl.com/ypdsx7we**
(CTIO/NOIRLab/DOE/NSF/AURA, T.A. Rector (University of Alaska Anchorage/NSF NOIRLab), M. Zamani and D. de Martin (NSF NOIRLab), Anirudh Chiti, Alex Drlica-Wagner)

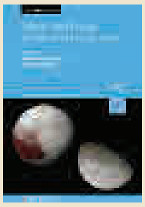
RAS Library
New books

The RAS Library and Archives are open from Tuesday to Friday. Check ras.ac.uk/library/opening-times for the latest updates on opening hours.

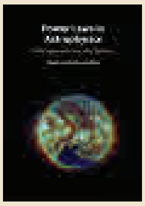


Lintott C *et al.* 2026 *Cosmos: The Art of Observing Space* (Sansom & Company, Bristol)

Huang H-F 2025 *Commercial and Sublime: Popular Astronomy Lectures in Britain, 1780–1860* (University of Pittsburgh Press, Pittsburgh, Pennsylvania)



Luspay-Kuti A & Mandt K eds 2025 *Triton and Pluto: The long lost twins of active worlds* (IOP, Bristol)



Aschwanden M 2025 *Power Laws in Astrophysics: Self-Organized Criticality Systems* (Cambridge University Press, Cambridge)

Plebanski J & Krasinski A 2024 *An Introduction to General Relativity and Cosmology* 2nd edn (Cambridge University Press, Cambridge)

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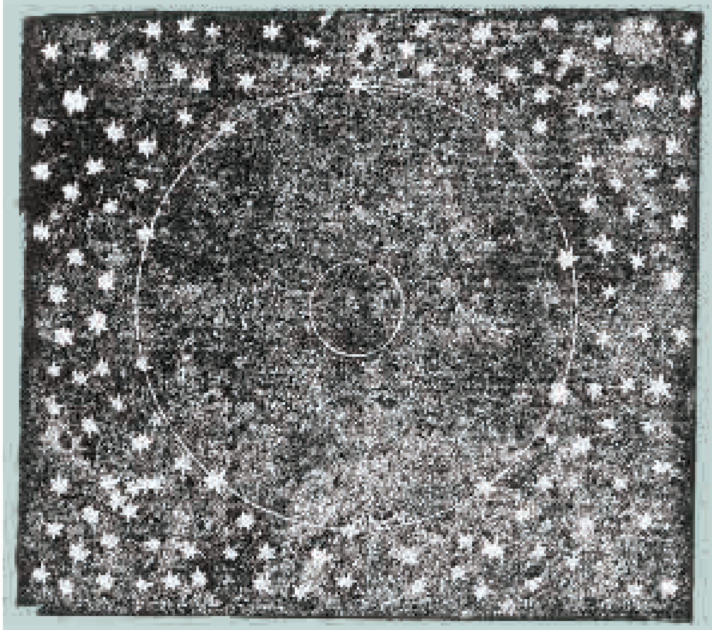


Pick of the RAS archive
Kepler's dark skies

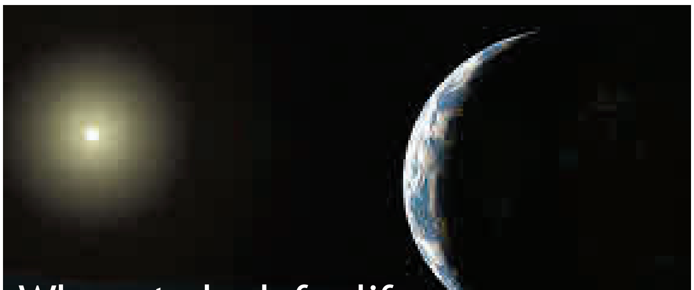
This diagram from Johannes Kepler's *Epitome of Copernican Astronomy* (1618) shows our solar system encircled by the fixed stars. Long before Heinrich Wilhelm Olbers published the paradox that now bears his name, earlier astronomers like Kepler had grappled with the same conundrum: if the universe were infinite and static, every line of sight should end on a star – yet the night sky is dark. Kepler took this as evidence that the universe is not infinite. **ras.ac.uk/library** (RAS/SPL)

Space weather could hide technosignatures

Turbulent plasma around host stars could make alien signals from their planets difficult to detect. That's according to a study by Vishal Gajjar (SETI Institute) and Grayce Brown (University of California Berkeley), which considered narrow-band radio technosignatures. The researchers showed how plasma density fluctuations in stellar winds, as well as occasional eruptive events such as coronal mass ejections, can distort radio waves near their point of origin, effectively smearing the signal's frequency and reducing the peak strength. A paper appears in *The Astrophysical Journal*. **tinyurl.com/y68cmy65**

DART impact diverted Didymos

Final analysis of NASA's DART (Double Asteroid Redirection Test) mission has confirmed that a kinetic impactor can be an effective planetary defence technique. A study, led by Rahil Makadia (University of Illinois Urbana-champaign), shows the impact with Didymos ejected so much material from the binary system that it also changed the binary's orbital period around the Sun (lasting about 770 days) by 0.15 seconds. That small change, given enough pre-warning, is enough to remove the threat of impact. The study appears in *Science Advances*. **tinyurl.com/3urkdzaz**



Where to look for life

Life exists on our rocky planet, so rocky exoplanets are good candidates for life. Abigail Bohl (Cornell University) and colleagues have pinpointed 45 rocky worlds that may support life in the usual habitable zone, and another 24 in a narrower 3D habitable zone. The study, published in *Monthly Notices of the Royal Astronomical Society*, addresses whether an exoplanet needs to stay in the habitable zone or can cross in and out of it and still remain habitable. **tinyurl.com/ycfs4hpj** (Gillis Lowry)

Deep magma ocean

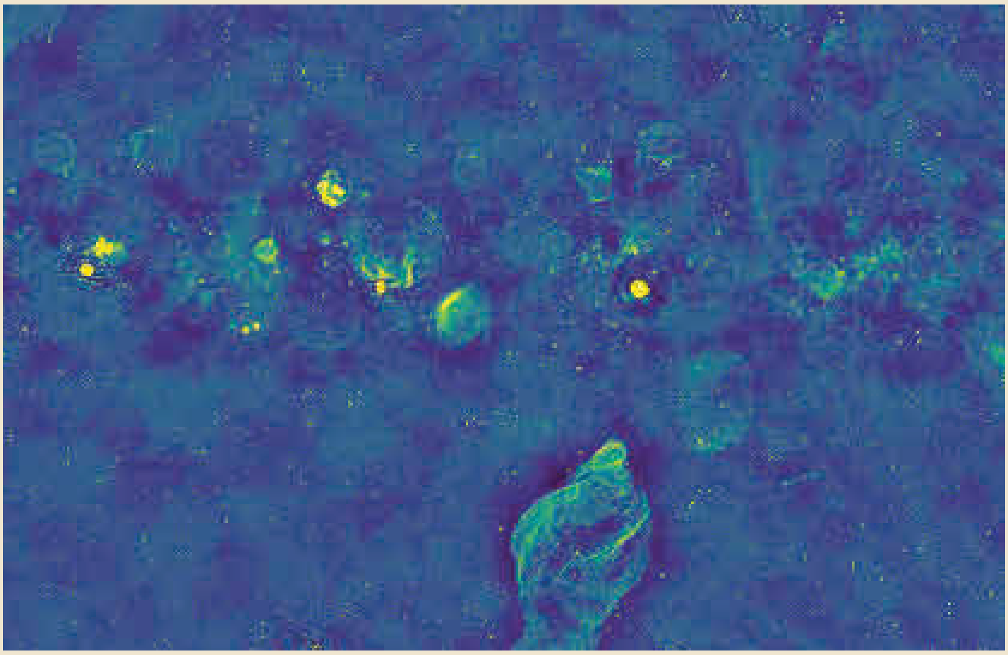
Harrison Nicholls (University of Oxford) and team have reconstructed a history of exoplanet L 98-59 d from shortly after its birth to the present day – a span of nearly five billion years. The results reveal that the mantle of L 98-59 d is likely molten silicate (similar to lava on Earth), with a global magma ocean thousands of kilometres deep. The research appears in *Nature Astronomy*. **tinyurl.com/34knb3fy**

Moon magnetism rarely strong

Claire Nichols (University of Oxford) and colleagues have reconciled data indicating either a weak magnetic field early in the history of the Moon, or a strong one. The team found that for brief periods, lasting less than 5000 years, the early Moon had an extremely strong magnetic field – even stronger than Earth's. Analysis revealed that the melting of titanium-rich material close to the Moon's core temporarily generated a very strong magnetic field. The Apollo samples over-represented these brief intervals, because the missions preferentially landed among mare basalts. A report appears in *Nature Geoscience*. **tinyurl.com/5n8h5s8h**

LOFAR's sky map

Astronomers using the Low Frequency Array (LOFAR) have unveiled an exceptionally detailed radio sky map, revealing 13.7 million cosmic sources and delivering the most complete census yet of actively growing supermassive black holes. The LOFAR Two-metre Sky Survey (LoTSS-DR3) also allows researchers to explore particle acceleration, cosmic magnetic fields and star formation over time. Timothy Shimwell (ASTRON) and colleagues present the preliminary results in *Astronomy & Astrophysics* **tinyurl.com/58czdwjn** (ASTRON/LOFAR)



White dwarf X-ray source

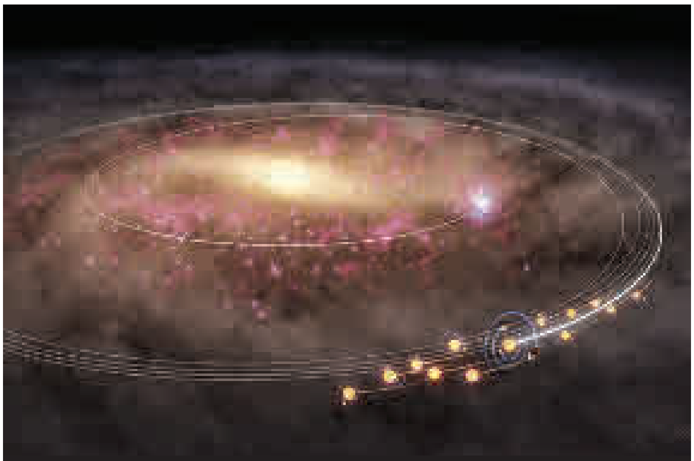
Astronomers have determined the origin of the mysterious X-rays from Gamma Cassiopeia. Observations with the XRISM telescope have allowed Yaël Nazé (University of Liege) and colleagues to attribute this emission to the white dwarf orbiting the Be-type star. This is the first evidence that the ultra-hot plasma responsible for the X-rays is associated with the compact companion, and not with the Be star itself. A paper was published in *Astronomy & Astrophysics*. **tinyurl.com/4fydjkxw**

A magnetar is born

Joseph Farah (University of California, Santa Barbara) and team have become the first to observe the birth of a magnetar. Changes in brightness from supernova SN 2024afav suggest a misaligned disc of material around a central magnetar. This is a result of an effect known as Lense-Thirring precession; the first time general relativity has been needed to describe the mechanics of a supernova. The study appears in *Nature*. **tinyurl.com/3wstz6nx**

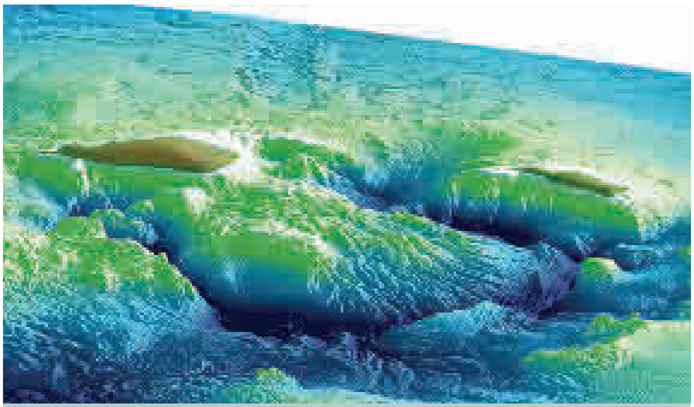
Neutron star-black hole binary was born eccentric

A new study corrects the masses of the neutron star and black hole in gravitational-wave event GW200105. Gonzalo Morras (University of Birmingham) and team find no compelling evidence of precession, indicating that the eccentricity was imprinted by its formation rather than by spin. This is convincing proof that not all neutron star–black hole pairs share the same origin. A paper appears in *The Astrophysical Journal Letters*. **tinyurl.com/mryxkwnc** (University of Birmingham)



Magma chamber refilled

A new study of the Kikai caldera (Japan) has found that there is a region of magma directly underneath the volcano that erupted 7300 years ago. The extent and location indicates that this is the same magma reservoir that supplied the previous eruption. This magma is likely not a remnant of that eruption, but new material instead. Akihiro Nagaya (Kobe University) and colleagues present the results in Communications Earth & Environment **tinyurl.com/3d2m2yzk** (SEAMA Nobukazu)



Sun in mass stellar migration

The Sun escaped from the galactic centre in a mass migration of stellar twins. That's according to a paper by Takuji Tsujimoto (NAOJ) and colleagues in *Astronomy & Astrophysics*. The conclusion comes from an analysis of the distribution of ages of solar-like stars in the Gaia dataset. They found a group of stars around the same age as the Sun, at around the same distance from the galactic centre. But they could not have escaped the galactic centre if the Milky Way's central bar existed at the time; thus the study also puts constraints on when the bar formed. **tinyurl.com/yvfxcc9w** (NAOJ)

Fellows among EAS medals 2026

Three RAS Fellows have been awarded prizes by the European Astronomical Society. Prof Gillian Wright of the UK Astronomy Technology Centre received the Tycho Brahe Medal for her leadership in the development of the Mid-Infrared Instrument on the JWST. Prof Rashid Sunyaev of the Max Planck Institute for Astrophysics received the Fritz Zwicky Prize for his work on the cosmic microwave background and disk accretion theory. Dr Graeme McGee of the University of Glasgow won the MERAC prize for the best doctoral thesis in new technologies (multi-messenger). **tinyurl.com/y5kx7rcc**

Read Allan Chapman…

We were sorry to hear of the death of astronomical historian Allan Chapman, a long-term supporter of *A&G* and a prolific contributor! From Allan's work we discovered: a plan for a mission to the Moon by boat, four centuries ago; Mary Somerville's surprising vocabulary; and the women-friendly world of Victorian astronomy societies. Read a collection of the articles he wrote for us on the *A&G* webpage. **tinyurl.com/m9wk6szy**

…Observe Allanchapman

On 23 February, the International Astronomical Union announced an asteroid in memory of Allan Chapman; he was nominated by Neil Haggath of Cleveland and Darlington Astronomical Society. The main belt asteroid 1984 BZ6 is now (13490) Allanchapman, with the citation recording him as "an eminent British historian, and a world-renowned authority on the history of science… a prolific author and astronomy populariser". This object was discovered in 1984 by an observer on Palomar Mountain and you may look it up at: **tinyurl.com/yfj4x28m**. **tinyurl.com/3e9wwx6f**

Quantum Big Bang test?

Ruolin Liu (University of Waterloo) and colleagues have developed a new way to understand how the universe began, potentially changing what we know about the Big Bang and the earliest moments of cosmic history. The universe's earliest expansion may, the team suggest, emerge directly from quantum gravity. Using Quadratic Quantum Gravity, which remains mathematically consistent even at extremely high energies, the team predicted a minimum amount of primordial gravitational waves, which may be detectable in upcoming experiments. A paper appears in *Physical Review Letters*. **tinyurl.com/5n6awutt**

Baby heliosphere from Chandra

Astronomers have detected an 'astrosphere' around a young solar-like star, an analogue of the Sun's heliosphere. Casey Lisse (Johns Hopkins University) and team, publishing in *The Astrophysical Journal*, report on new Chandra observations. HD 61005 is producing X-rays as the stellar wind runs into cooler interstellar dust and gas that surrounds the star. The 'astrospheric bubble' completely surrounds the juvenile star. **tinyurl.com/4patyahc**

Massive star direct to black hole

The star M31-2014-DS1 was one of the most massive and luminous stars in the Andromeda Galaxy, before it faded from view several years ago. Publishing in *Science*, Kishalay De (Flatiron Institute) and team have now shown the star collapsed directly into a black hole. The study presents the most complete observational record ever made of a star's transformation into a black hole, allowing the researchers to construct a comprehensive physical picture of the process. **tinyurl.com/y48kvzxp**

Potentially useful pulsar

Karen Perez (Columbia University) and colleagues have identified a 8.19-millisecond pulsar candidate near Sagittarius A*, at the heart of the Milky Way. If confirmed, the object could provide unprecedented tests of General Relativity. A paper appears in *The Astrophysical Journal*. **tinyurl.com/r3uavufc**

Ancient plates revealed

A new study has revealed the oldest evidence of tectonic plate movement, about 3.5 billion years ago. Researchers used palaeomagnetism on samples from more than 100 sites. The researchers, led by Alec Brenner (Harvard University), also discovered the oldest case of a geomagnetic reversal. The study appears in *Science*. **tinyurl.com/y3926bxc**

Multiple mergers make for a giant

Nearby spiral galaxy NGC 1365 began as a small galaxy and slowly grew into a giant via multiple mergers with smaller dwarf galaxies. Lisa Kewley (Centre for Astronomy, Harvard) and team made this conclusion based on 20000 simulations of the merger and growth history, and a comparison with the galaxy's oxygen distribution. The study was published in *Nature Astronomy*. **tinyurl.com/mt9vaydy**

Scottish CubeSats show the way

Three Scottish-built small satellites were launched by ESA as part of a programme to test laser communication between spacecraft and support technology for near-real-time data delivery and decision-making. Two were produced by ACC Clyde Space and one by Spire Global UK; they were produced with ESA support intended to develop the UK's emerging high-volume, low-cost satellite production and operations capability. **tinyurl.com/trhtsssz**

Radio zebras? Interference

The Crab Pulsar's radio 'zebra-stripes' are caused by an imbalance of forces. Writing in *The Journal of Plasma Physics*, Mikhail Medvedev (University of Kansas) has shown that the combination of a defocusing magnetospheric plasma wave and a focusing gravity wave create in-phase and out-of-phase interference bands of radio-wave intensity. This creates the bright, distinct striped pattern seen in radio waves. **tinyurl.com/4j7b7udr**

The RAS New Fellows

The following were put forward for RAS Fellowship on 13 March 2026

Aleyana Adamson, Birmingham
Jordan Allen, Scarborough
Jacob Ayre, Tyne and Wear
Bryce Bolin, Seattle, USA
Evie Cushing, Bristol
Adam Dillamore, Ware
Sohini Dutta, Manchester
Thomas Dyer, Nice, France
Emily Frank, Armagh
Jenni French, Birmingham
Alexander Gordon, Newtongrange
Homer Dàvila Gutiérrez, San Jose, Costa Rica
Susanne Hoffmann, Jena, Germany
Christian Hotgarth, St Andrews
Swasti Jain, Jabalpur, India
Edward Kilgur, Lake Country, Canada
Kassidy Kollman, Plainsboro, USA
John-Ryan Lawrence, Kingsville, USA
Alexander MacManus, Salisbury
Bigi Michele, Massa, Italy
Luke Morriss, Leeds
Oscar Murray, York
Eshaan Niraj, London
Ann Njeri, Salford
Aidan Payne, Ramsgate
Apurva Pillai, Manchester
Mohammed Rana, London
Penelope Shaw, Chislehurst
Maria Tsinidi, St Andrews
India Uppal, Liverpool

Obituaries

Roger Maurice Bonnet (1937-2026) A giant of European space science

"He conceived and implemented Horizon 2000, the science plan that reshaped Europe's ambitions in space and underpins ESA's programme to this day"

Roger-Maurice Bonnet, who died on 19 January 2026 aged 88, was one of the principal architects of European space science. He firmly believed that Europe required a long-term, balanced space science programme. As ESA's director of scientific programmes, he conceived and implemented Horizon 2000, the science plan that reshaped Europe's ambitions in space and continues to underpin ESA's programme today.

Born in December 1937 in Dourdan, south-west of Paris, Roger studied physics and astronomy at the University of Paris, graduating in 1961. His subsequent doctoral research in solar physics was hands-on, developing and mounting instrumentation on sounding rockets and balloons, and took him directly into involvement in the earliest French space activities. In 1963, he launched the first French space astronomy experiment aboard the Véronique rocket, from Hammaguir, Algeria. Based on this work, alongside UV imagery and spectroscopy of the Sun, he was awarded a doctorate by the Sorbonne in 1968.

In the aftermath of the political upheavals of 1968, in which he took enthusiastic part, Roger established an independent astrophysics group – under the Laboratoire de Physique Stellaire et Planétaire – that gained recognition from both the French research organisation CNRS, and the space agency CNES. The group flourished through the 1970s, contributing instruments to NASA missions OSO-6 and OGO-8, as well as to the French D2A satellite, renamed Tournesol. Roger was appointed director of the laboratory in 1978.

From 1978 to 1981, he served on ESA's Space Science Advisory Committee, a period characterised by a reduced science budget, competition with applied programmes, and the cancellation of US funding for the joint Ulysses solar polar mission. These challenges likely forged Roger's conviction that Europe needed an independent stance in space science.

When he became director of scientific programmes on 1 May 1983, some eight years after ESA's creation, Roger inherited a full programme on a dangerously reduced budget: IUE and ISEE-B were operating; Exosat was just launched; HST, Ulysses, Hipparcos and Giotto were in development; and the Infrared Space Observatory was on the starting block. Pressure was also mounting to prioritise commercial and applied programmes. Within months of taking office, he issued an unprecedented 'call for mission ideas' to the space science community, establishing a broad-based survey committee to define priorities. The result, published in December 1984 as *Space Science – Horizon 2000* (ESA 1984), united the European space science community with its 20-year, phased programme spanning all major areas of space science. Today, ESA's Science Programme is widely regarded as the agency's backbone – a legacy that owes much to Roger's determination and persuasive leadership.

In 1997, his directorate was also tasked with designing Europe's future Earth observation strategy beyond Envisat. The resulting plan introduced a series of smaller, focused missions, alongside satellites dedicated to long-term Earth monitoring. The latter evolved into the space component of the EU's current Copernicus programme.

Roger retired from ESA in 2001, moving to CNES as associate director for Science. In 2002, he became the president of the Committee on Space Research (COSPAR), reinforcing his longstanding belief that space science should have no borders. Even at the height of the Cold War, COSPAR was where Russians met Western scientists, and in 1986, Roger was instrumental in creating international coordination for the ESA, Japanese and Russian probes sent to Comet Halley. After the failure of the first Ariane 5 launch, he played an important part in rebuilding the Cluster spacecraft and organising Russian Soyuz launches. Soyuz became the joint Russian-European system launching from ESA's Kourou site, eventually taking ESA spacecraft to Mars and Venus. He also pioneered cooperation with China, with a Cluster data centre established in Beijing.

From 2001 to 2006, Roger served as a special adviser to ESA's director general on planetary exploration, contributing to the programme that would produce the Rosalind Franklin rover, currently awaiting launch to Mars. From 2003–10, he was executive director of the International Space Science Institute in Bern, Switzerland, which alongside his COSPAR presidency, kept him firmly in contact with the global space science community.

Roger was an Officer of the French Légion d'Honneur and received numerous international distinctions, including NASA's Public Service Medal, the CNES Silver Medal, the COSPAR Award, the Von Karman Award of the International Academy of Astronautics and the Gold Medal of the Chinese Academy of Sciences.

By seizing the opportunity in 1983 to redefine Europe's scientific ambitions in space, Roger secured his place in space history. His persuasive powers were critical in rebuilding ESA's science budget and his long-term planning of Horizon 2000 and its successors changed European space science and strongly influenced its development worldwide. Space scientists will always owe him a debt.

AUTHOR

David Southwood is a space scientist and senior research investigator at Imperial College London. He was director of Science and Robotic Exploration at ESA from 2001–11.

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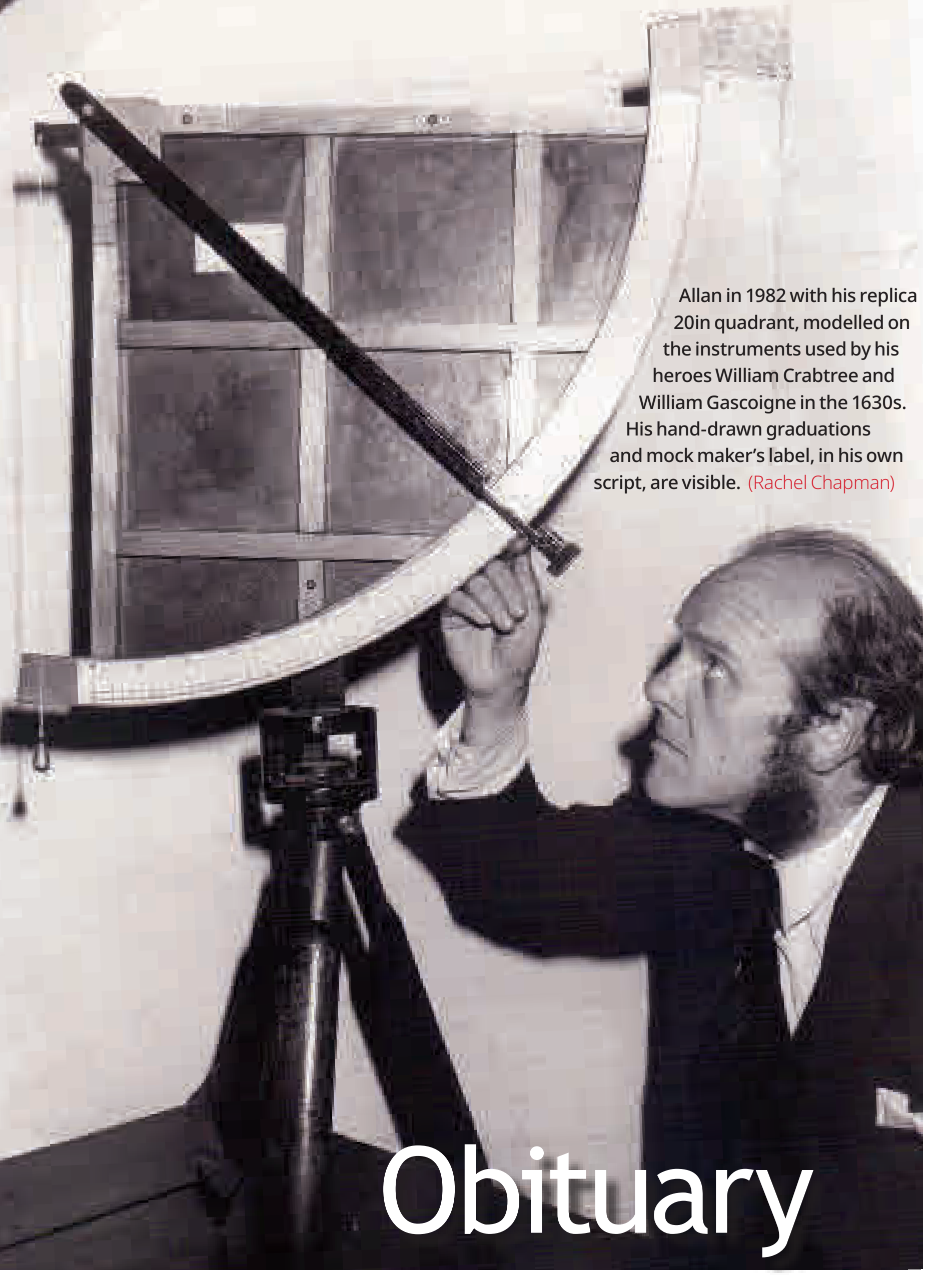
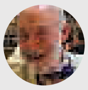


Allan in 1982 with his replica 20in quadrant, modelled on the instruments used by his heroes William Crabtree and William Gascoigne in the 1630s. His hand-drawn graduations and mock maker's label, in his own script, are visible. (Rachel Chapman)

Obituary

Dr Allan Chapman (1946-2026) Doyen of History of Astronomy, inspiring science teacher and charismatic lecturer

AUTHOR



Roger Hutchins was mentored by Allan while researching for his DPhil in 1990, and was inspired to seek the social context behind careers. Their friendship grew in Oxford and within the SHA.

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Dr Allan Chapman never held a stipendiary academic post. Leaving school without qualifications, he forged a freelance career in academia, gained three doctorate degrees, published widely and had a host of friends. In 2025, as failing health curtailed his travels and lecturing, he began updating his CV and drafting his memoir ahead of his 80th birthday. It was not to be. On 21 January, he had a severe fall and died of cardiac arrest aged 79.

Born in May 1946 in Pendlebury, a small colliery town near Salford, Allan lived in a pit cottage then a council house. The Secondary Modern curriculum developed his woodwork and metalwork skills. Inspired by his grandfather's fascination with "the idiosyncrasies of how individuals overcome technical obstacles", he built his first telescope at 11 and founded a school astronomical society. Convinced that to understand instruments one must construct them, he pursued watch-making skills.

Allan had a near-photographic memory, boundless curiosity, and was charmingly eccentric. He worked in a public library while studying at night school, earning a place to read History at Lancaster University. Arriving aged 23, and already sartorially distinctive, he gained a Queen's Scholarship. There, in 1970, he met Peter Hingley; they established the Astronomical Society and built a roof-top observatory.

Graduating with a first-class degree, Allan matriculated from Wadham College, Oxford, in 1972, was elected FRAS in 1973, and completed his DPhil, Critical Angular Measurement in Astronomy 1500–1850, in 1978. It was published as *Dividing the Circle* (1990); the Faculty of History still note it as "a standard work in the history of scientific instrument making".

Allan began writing and lecturing to societies, and after 1976 he did some TV and radio broadcasting. He gave tutorials and lectures for a new History of Science course at Oxford from 1974 until 1988. In 1978, he began supervising Chemistry Part II historical theses, accruing almost 100 by 2022. He was made a member of the Faculty of Modern History, and from 1975 until 1992 he was a tutor and later senior tutor at the Centre for Medieval and Renaissance Studies (CMRS); Allan's freelance teaching career spanned some 45 years.

For thesis research he replicated a cross staff, quadrants and nocturnals. He studied the Royal Greenwich Observatory collection and set himself to replicate John Flamsteed's lost instruments, building a half-scale replica of his 7ft mural quadrant. CMRS enabled him to build a replica meridian observatory in the roof of St Michael's Hall, where he used the instruments under conditions similar to those of the originals in order to replicate their technology and master, to some degree, their astronomical art.

Allan's fascination with where the spark of genius appeared meant that social context distinguished his work. Pursuing "how a particular person, discovery, or technological innovation fits into the wider picture", he spent two decades trawling archives. He identified the 'Grand Amateurs' who patronised instrument makers, thereby driving technology and seeking status within the Royal Society and Royal Astronomical Society, and the subservient rest who loved the sky yet were excluded by learned societies holding meetings at 3pm, which only gentlemen could attend. All were the grist for his masterwork *The Victorian Amateur Astronomer* (1998). Prof Robert Smith assessed: "This fantastic book resulted from the remarkable depth and originality of the research that enabled Allan to rescue many ignored figures from 'the enormous condescension of posterity'. ... Here we see a master historian in full command of his craft."

That rare sensitivity guided Allan's whole output, and the ethos of the Society for the History of Astronomy (SHA), of which he was co-founder in 2002. For Allan, genius could appear anywhere, and social barriers deserved scrutiny as the obstacles that merit overcame.

Allan began lecturing in his teens, first to the new Salford Astronomical Society, "who first taught me how to look at the sky". From the 1960s until the Covid pandemic in 2020, he lectured at some 30 astronomical societies annually across Britain and abroad. He addressed leading academic institutions and the smallest local clubs with equal enthusiasm – always without fee, requesting only rail fare, hospitality and tea. His desire to share knowledge and inspire others was reflected in his friendships with David Dewhirst and Peter Hingley, and in his close association with those popularising astronomy, notably Patrick Moore, Heather Couper and Nigel Henbest. Allan became close to Patrick Moore while *The Sky at Night* was supreme and latterly replaced Patrick as keynote speaker at Leeds Astrofest.

Allan's writings, lectures and TV appearances shaped public understanding of the history of astronomy. Many young scholars can trace their research origins to one of Allan's talks. He also lectured extensively in the USA and Europe. His precisely timed presentations were based upon his own research and delivered entertainingly, without notes, alongside clunky 35mm slides.

Allan also became an historian of medicine, which eventually occupied a third of his time. From 1982, he lectured annually to the American Medical School and dedicated his book *The Medicine of the People* (2018) to his maternal grandparents, whose folk remedies were his starting point.

Between 1982 and 2025 Allan published 18 books – eight of which were academic, including two on medical history, plus three reprints – in addition to booklets, more than 110 journal articles, 69 feature articles in *Astronomy Now*, and many others in magazines and newspapers. Numerous TV programmes included the series *Gods in the Sky* (Channel 4) and *Great Scientists* (Channel 5).

Some 40 years ago, Allan set himself to understand George Airy, Astronomer Royal (1835–81), resulting in his short masterpiece *Sir George Biddell Airy, Astronomer Royal, Experimenter, and Public Servant* (2023). He faced down Airy's detractors and concluded simply that "Apportioning blame in the Neptune saga achieves nothing; men of very different personalities were involved". His final chapter, 'The Airy's at Home', empathetically restored humanity to a man often portrayed abstractly.

Allan's half-scale replica of Flamsteed's quadrant (above), and his replica of Hooke's microscope (above right) (Rachel Chapman; David Stumpp)

Below: **Allan with Rachel and Patrick Moore at the South Downs Planetarium, 2007, celebrating almost 50 years of *The Sky at Night*. The Madame Tussauds waxwork of Patrick was given to the Planetarium.** (Martin Mobberley)

Recognition of Allan's work was marked by the 2015 award of the RAS's Jackson-Gwilt Medal "for his personal research into the history of angular measurement, early British Astronomy and the role of the Victorian amateur, his immensely important role in stimulating an interest in such research among others, and not least in helping to promote the founding of the SHA". He was only the third historian in 118 years to receive the award.

"The lad from Pendlebury Secondary Mod" was no longer remedial but had achieved MA, DPhil, DUniv (University of Central Lancashire; 2004), DSc (University of Salford; 2010), FRAS, Visiting Professor of History of Science at Gresham College (2004–11), RAS Jackson-Gwilt Medallist, and Vice-President (2002) and President (2012) of the William Herschel Society. Allan held honorary presidencies of six astronomical societies.

Through a shared love of choral church music he met Rachel Woodrow, whom he married in 1991 and who had a profound influence upon his life and work. Allan emphasised that his prolific writing output was crucially enabled by the editorial and word-processing skills of his classicist "scholar and best friend" Rachel, to whom he dedicated his recent books.

His Christian faith, developed in the 1980s, informed his interest in the dialogue between religion and science and led to his book *Slaying the Dragons: Destroying Myths in the History of Science and Faith* (2013). He watched the self-inflicted contortions of the Church of England with some incredulity.

Highly sociable, with a mischievous sense of humour, Allan was aware of his gifts of memory, eloquence and delivery, and enjoyed sharing and mentoring. He enjoyed craft skills, collected old cameras, loved steam trains and train sets, and tinkered with a collection of timepieces. He loved classical and especially church music, had a keen eye for architecture, and read history and biography. He attended the Blackpool Illuminations every year, like a pilgrimage, and often rode the trams.

The IAU swiftly announced naming main belt asteroid (13490) Allanchapman = 1984 BZ6 for him. Tributes include that from Stuart Clark: "Allan was one of the foremost historians of astronomy who has ever lived. … We are all infinitely richer for the life's work that he leaves behind." ●

Cutting the future?

Past and current RAS presidents **Mike Lockwood** and **Jim Wild** respond to yet another STFC funding crisis – one that threatens the future success of both our research community and the national economy.

Once again, we face a research council funding crisis and, once again, it is the careers of younger scientists that are taking the brunt of it. This is a direct result of how UK science funding is structured. At present, when a research council budget is stressed, whether by over-commitment, exchange-rate fluctuations, inflation, cuts or flat-cash budget allocations, too often the only available way to balance the books is to reduce the 'blue skies' grants line. This may be a short-term fix, but it does lasting and serious damage to career development and to the transfer of fundamental research into wealth creation and innovation.

The Government aspires to be a 'science superpower', which requires not only world-class facilities but also first-class scientists to use them. Crucially, the timescales of facility readiness and human capital development must be aligned. Major facilities take many years, often over a decade, to move from concept to full operational capability, and early-career scientists typically take six to ten years from starting a PhD to becoming fully independent researchers.

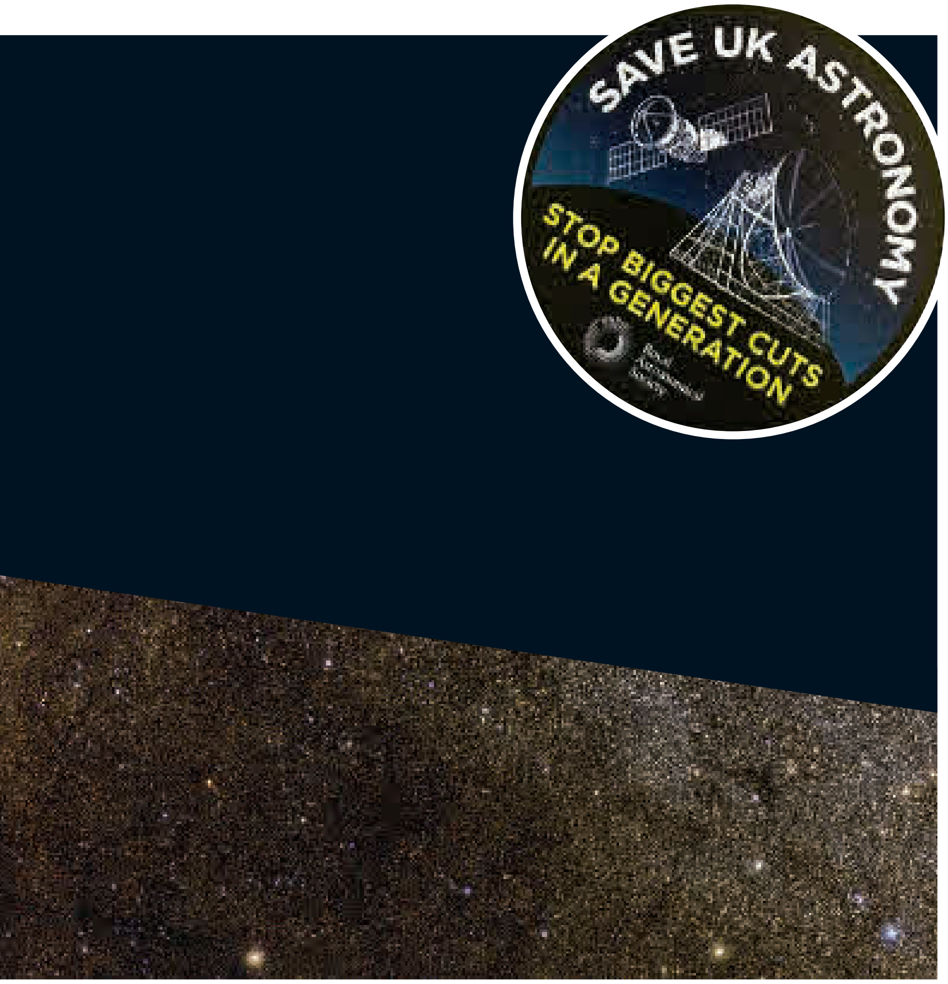
We must also look beyond the research to what the nation as a whole stands to lose, because far more than national scientific prestige is at stake. Scientific research and facilities generate value outside academic research through the skills and techniques that they develop. If we fail to support the pipeline of people during the long gestation periods of facilities, the UK loses much of the knowledge transfer, skills diffusion and economic return such facilities are meant to enable. Evidence shows that early-career scientists trained on STFC-supported projects convert infrastructure, techniques and discoveries into innovation, economic growth and high-value skills. A significant proportion – around 30% – of UK astronomy and physics PhD graduates move into the private sector, many into roles in software, data science and operational research, bringing advanced analytical and computational skills to high-growth industries. The problem is that young scientists cannot develop these transferable skills if funding periodically dries up. They are forced to leave either science or the country – and once they have left, persuading them to return becomes extremely difficult, especially if the financial support they need remains volatile.

"A 'science superpower', requires not only world-class facilities but also first-class scientists to use them"

Catching the Big Bang

What we have said is always true and important – but it is especially critical at times when the nation requires particular skills to meet major societal or economic challenges. A striking historical example is the deregulation and computerisation of the City of London's financial markets in the mid-1980s. The financial 'Big Bang' of 1986 created a huge demand for experienced and skilled computing professionals, especially those familiar with UNIX-based multiuser systems, networking, and data processing. In very large part, that need was met by individuals who had, up to that point, been involved in fundamental research and research computing. The period of particularly acute demand for these skills spanned roughly 1983–87, encompassing the lead-up to, and aftermath of, the Big Bang.

Now we face an analogous situation with artificial intelligence. Both to exploit the opportunities AI presents and to help solve the complex challenges it poses, the country will need people with deep experience in machine learning (ML), data analytics, model validation, and systems integration. AI and ML are already widely used in fundamental science, and learning how to use them safely and wisely is a steep curve that many



ESO/VISTA

young scientists are actively navigating. The skills that drive breakthroughs in research are those that will be essential for national capability in the coming decade.

In response to the present crisis, RAS Council has tripled the number of research fellowships we offer. This is a small drop in the ocean compared with the scale of job losses that the levels of grant cuts under discussion will cause; however, it is a gesture of our support for early-career scientists. The box 'Reaction and action' lists other actions the RAS has taken to try to prevent the loss of a generation of scientific talent.

Wealth creation in the modern world is much less about natural resources than it used to be, and much more about skills and innovation. Hence structural change to stop this cyclic loss of talent is vital. After the previous crisis on this scale in 2008, Lord Drayson and others tried to put measures in place to prevent recurrence. That those measures were either abandoned or circumvented points to the need for more substantial systemic reform of how UK research funding protects people and skills as well as projects and infrastructure.

Astronomy and space science are uniquely important in setting young children on a path towards careers in science or technology. Both of us know well the great power they have to inspire young people and so we both regularly give talks in schools and colleges in which we can honestly tell of how rewarding and fun a life in science can be. However, it is deeply troubling not to be able to be so open about how it is also an insecure life that can be blown off course through no fault of the young scientist. Reorganising science funding to reduce the jeopardy that over-commitment generates for young careers would remove a major dissuading factor that robs the nation of so much of the talent it needs.

"To be clear, we are not facing a small leak in the talent pipeline; this is a major rupture"

Reaction and action

Since the proposed cuts surfaced in January, the RAS has moved quickly and decisively to safeguard UK astronomy. We are confronting policymakers and fundholders with the stark reality of the catastrophic damage these cuts will cause, particularly to the futures of early career researchers. We are coordinating with key partners, including the Institute of Physics (IoP) and community groups such as the Astronomy Forum, IoP Heads of Department Group, MIST Council and UK Solar Physics, and have joined forces with the Astronomer Royal for Scotland and other influential figures.

Our strategy includes:

- **Political pressure:** briefing the Science, Innovation and Technology Committee and the media; supporting a direct ministerial open letter; and equipping MPs with targeted parliamentary questions that were put to ministers Liz Kendall and Lord Vallance, Astronomer Royal and STFC executive chair Michele Dougherty, and UKRI chief executive Ian Chapman. We have also voiced our concerns to Lord Vallance, who acknowledged that some missed grant rounds and delayed starts were mistakes that needed to be rectified, but has not yet commented on the wider cuts to funding for early-career researchers.
- **Strategic transparency:** filing five Freedom of Information requests to expose UKRI's budget breakdowns and the removal of critical funding protections. We have also provided evidence to counter misleading political spin that blue-sky research is not being cut.
- **Community mobilisation:** uniting university heads and community leaders, launching 'Save UK Astronomy' campaign stickers, creating an open letter for teachers, and providing Fellows with the tools to lobby their MPs directly.
- **Direct investment:** tripling the number of RAS Research Fellowships as a gesture of our support for the next generation of researchers.

Can you help? We have established a high-level action group to execute this strategy.
To contribute vital insights or strategy ideas, please email saveukastronomy@ras.ac.uk.

At the time of writing, despite intense lobbying, no clear solution to the present crisis has emerged. Any effective action needs to include restoration of the number of post-doctoral researchers supported by the grants line that has already been cut by 30%. To be clear, we are not facing a small leak in the talent pipeline; this is a major rupture. There are also serious concerns that we will not garner the benefits of investment made over several decades by not funding the next generation of instruments for major facilities. Compared to other areas of Government funding, the cost of a solution that keeps our national aspiration to remain a science superpower alive is minuscule. Beyond that we will still need systemic reform to prevent a recurrence. There is a saying about never wasting a serious crisis – maybe the present one can finally bring much-needed reform.

Q&A

GJI Student Prize winners

This year, the standard of entries to the *GJI* Student Prize was so high that three joint winners were chosen. Indra Bains caught up with one of them to ask about his research interests and future plans.

Masayoshi Someya

Congratulations on winning the 2025 *GJI* Student Prize. Tell us what your winning paper – 'Physics-Informed Neural Networks for Offshore Tsunami Data Assimilation' – was about.

The paper models the tsunami propagation process using Physics-Informed Neural Networks (PINNs), a novel framework for solving partial differential equations. By combining this approach with data from offshore tsunami observation networks, the tsunami wavefield can be reconstructed.

What is the significance of this award to you?

This paper is based on my master's thesis. I am delighted that my efforts during my master's programme have been recognised, and I am grateful to my supervisor and the many others who supported my research. I am currently a PhD student and continue to work on modelling tsunami propagation using machine-learning techniques.

What first got you interested in geophysics?

I was originally interested in geophysics, particularly seismology, but experiencing the 2011 Tohoku earthquake seems to have determined my career path. I was in elementary school at the time, and watching experts comment on earthquakes and tsunamis on TV made me want to become a seismology researcher.

Can you describe a challenge you faced during the research for your paper, and how you overcame it?

In my lab, my work was a relatively new research direction, so there were many things we didn't know. I found myself asking questions like: how do I run the programme the way I want to, and what's the best way to process the data? I found that the quickest way to solve these problems was to talk to different people.

What do you hope other geophysicists will build on from your research?

One of my research themes, scientific machine learning, aims to advance numerical simulations by leveraging the power of AI. While numerous applications already exist in seismology, there are very few examples of its application to tsunami problems. My research focuses primarily on offshore tsunamis, and there is still much room for work on tsunamis near the coast. I hope my paper will inspire others to join this field and help push the research further.

Do you have any advice for other students hoping to publish in *GJI*?

It's important to discuss your manuscript thoroughly with your supervisor and revise it until you're satisfied with it – although we often still find mistakes after publication.

What are your plans for after your PhD?

I'd like to continue as a researcher in this field. There are still many topics that interest me. For example, how useful are tsunami observation data obtained near the epicentre for constraining earthquake source parameters? And from a disaster-prevention perspective, how quickly can such estimates be made? We need to maximise the use of data and develop flexible, easy-to-use numerical simulation methods. I believe AI will be indispensable for achieving this.

"We need to maximise the use of data and develop flexible, easy-to-use numerical simulation methods"

What is one big scientific question you'd like to help answer?

Is it possible to construct a unified source image using different types of data, such as seismic waves, tsunamis and crustal deformation? This has been a long-debated question in the field of inversion. Different data sets often yield different source models, and we don't understand whether these differences stem from the nature of the data itself or from the ways we model them. Contributing to the foundations for addressing these questions has always been on my mind.

What are your hobbies outside of research?

I enjoy using Google Street View to explore landscapes around the world. Japan is rich in natural beauty, but there are so many astonishing sights elsewhere that I'd never be able to imagine otherwise.

If you could instantly become an expert in something unrelated to your PhD, what would it be?

I've always wished I could become an expert in applied mathematics. When I see someone with a strong background in mathematics using novel concepts to solve problems, I really admire that and wish I could do the same. ●

AUTHOR
Indra Bains is editor of *A&G*.
Masayoshi Someya is a first-year PhD student at the Earthquake Research Institute, University of Tokyo.

Jim Dungey (in 1985) wielding a weather vane in the form of the schematic from his 1961 paper which introduced the concepts of magnetic reconnection and the open magnetosphere (Prof William Jeffrey Hughes)

1(b) Aurorae observed from the ISS on 20 August 2021 (NASA/ESA/Thomas Pesquet)

1(c) Aurora Australis on 11 September 2005, viewed by the IMAGE satellite, four days after a large solar flare (NASA/GSFC/Scientific Visualization Studio)

1(a) Northern lights over Iceland (AstroAnthony)

Dungey Lecture: Aurorae on Earth and other planets

Gabrielle Provan received the 2024 James Dungey Lecture for her contributions to planetary auroral studies. Here she summarises this research area, focusing on the scientific background and recent findings.

James Dungey is widely regarded as one of the founding figures in magnetospheric physics. This article explores how Dungey and his colleagues' research in the 1950s and 1960s on Earth's aurorae revolutionised our understanding of magnetospheric processes throughout the solar system. I will begin by examining Earth's aurora, then move on to those of Jupiter and Saturn. Along the way, I will trace the development of scientific hypotheses and models that have shaped current theories explaining the aurorae.

Earth's aurorae

The Aurora Borealis (northern hemisphere) or Aurora Australis (southern hemisphere) are nature's most spectacular light show. The aurorae can illuminate the polar night skies in a range of colours, predominantly green, but also reds and purples and shades thereof. Auroral activity will vary, meaning that the lights can change from faint greyish glows to dynamically bright displays in a matter of minutes. Figure 1a shows the aurorae observed from the ground in the northern polar regions, showing their brilliance and power.

Aurorae have been observed from Earth since ancient times, but in the modern era one of the most optimal vantage points is from space. From the International Space Station (ISS), for example, aurorae appear as shimmering curtains of light above the Arctic and Antarctic regions. The ISS orbits Earth at an altitude of

"Aurorae have been observed from Earth since ancient times, but in the modern era one of the most optimal vantage points is from space"

"In the Middle Ages, one theory suggested that the aurorae were caused by candles burning above the clouds"

approximately 402km (250 miles), passing through the planet's night side 16 times each day, providing astronauts with multiple opportunities to witness these breath-taking displays. An example of aurorae as observed from the ISS is shown in figure 1b. From higher-altitude spacecraft, the aurorae can be seen forming ovals around the poles. NASA's IMAGE satellite captured an example of the southern auroral oval, as shown in figure 1(c).

The thickness of the auroral oval is generally about 10° in latitude and its equatorial limit generally descends to about 75° to 65° geomagnetic latitude depending on magnetic activity. Occasionally, during strong magnetic storms, the auroral oval extends to lower latitudes. Intense aurorae are then observed in northern Europe and America. However, aurorae at low latitudes are relatively rare and only occur during strong magnetic disturbances.

The aurorae have fascinated humanity throughout history, inspiring myths, legends, and stories across cultures. The earliest known reference to the northern lights may be Cro-Magnon cave paintings in northern France. In Roman and Greek mythology, Aurora is the goddess of dawn and Boreas the god of the north wind, so aurora borealis literally means 'dawn wind'. In the Old Testament, the book of Ezekiel describes a 'whirlwind of fire' from the sky, which some interpret as a reference to the northern lights. Folklore from across the polar regions also features aurorae, such as the Finnish tale of the arctic fox whose tail brushes the sky, painting it with streaks of light.

Today we know that auroral processes occur on every planet or moon with both a collisionally thick atmosphere and a magnetic field strong enough to deflect the solar wind or plasma flow. Auroral emissions are produced by the impact of high-energy charged particles on the upper atmosphere, forming displays with a wide range of brightness and morphology. In this way, the aurora provides a visible projection of magnetospheric processes, allowing us to study global dynamics by remote sensing.

The path to this modern understanding, however, was long and imaginative. In the Middle Ages, one theory suggested that the aurorae were caused by candles burning above the clouds. A major step forward came in 1859, when Richard Carrington documented his observations of a solar flare (Carrington 1859), linking solar activity to geomagnetic and auroral effects: "While engaged in the forenoon of Thursday, September 1, in counting the spots on the solar disk, I was suddenly surprised at the appearance of a very bright white light, which broke out in two patches in the neighborhood of the largest group of spots…"

Figure 2a shows Carrington's diagram of sunspots, with two solar flares marked at A and B. About 18 hours later, a powerful coronal mass ejection (CME) from this flare reached Earth, causing one of the most intense geomagnetic storms ever recorded. The Earth's magnetic field fluctuated greatly, as recorded by magnetometers around the world. Figure 2b shows the magnetogram recorded at the Greenwich Observatory in London during the Carrington Event of 1859.

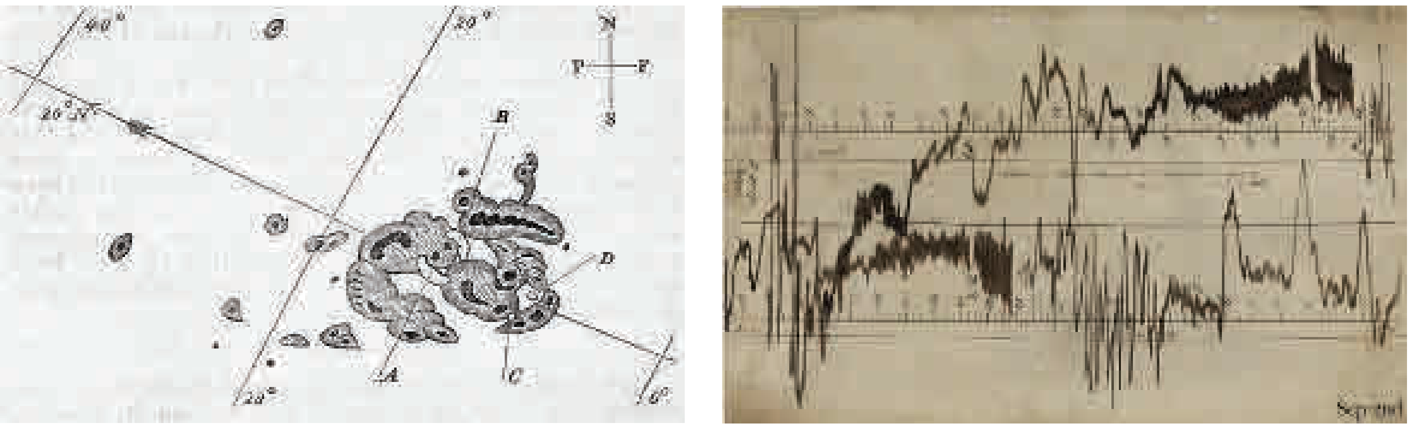
The geomagnetic storm produced aurorae that were visible as far south as the Caribbean. In some places, the aurorae were so bright that people could read newspapers by its light. The storm induced strong electrical currents in telegraph wires, causing some systems to fail completely while others operated without batteries due to induced currents. Some telegraph stations even caught fire. This was the first known report of 'space weather'.

In 1931 Sidney Chapman and Vincenzo Ferraro suggested that the Sun sends out huge clouds of charged particles, though overall electrically neutral. When these clouds envelope the Earth's magnetic field, magnetic storms, associated with disturbances in the Earth's magnetic field, occur (Chapman & Ferraro 1931). Chapman and Ferraro knew, of course, that the Earth contains a strong magnetic field which is approximately dipolar. It is worth noting that the Earth's magnetic dipole is currently 'upside down' so that the Earth's magnetic south pole is in the northern hemisphere and vice versa. Chapman and Ferraro suggested that the strong magnetic field of the Earth would hold off the 'clouds', creating a cavity where the Earth's magnetic field would be confined; this is now known as the Earth's 'magnetosphere'.

Discovery of the IMF

At this time, the Sun's solar wind, imbedded with the Interplanetary Magnetic Field (IMF), had not been detected. The IMF was only discovered in 1960 with the advent of the space age, when the spacecraft Pioneer V was launched with a magnetometer on board. The solar wind, though not that different to the clouds of plasma envisaged by Chapman and Ferraro, blows continually from the Sun into interplanetary space at velocities of hundreds of kilometres per second, and flows together with the IMF.

Even before the IMF's discovery, scientists including Fred Hoyle and his PhD student Jim Dungey had hypothesised its existence and terrestrial effects. In 1961, Dungey proposed that magnetic reconnection could occur where the IMF and Earth's magnetic field are anti-parallel. He suggested reconnection as the key mechanism for transferring mass, energy, and momentum from the solar wind into the magnetosphere. Dayside reconnection between southward directed IMF



2(a) Richard Carrington's diagram of sunspots observed on 1 September 1859 (Carrington 1859). (b) A magnetogram recorded at the Greenwich Observatory during the Carrington Event of 1859. (British Geological Survey) and the Earth's magnetosphere creates open field lines that are dragged into the nightside lobes by the solar wind, forming the 'magnetotail'. Oppositely directed lobe fields reconnect on the nightside, forming closed field lines that return sunward at lower latitudes. This global circulation is known as the 'Dungey cycle' and typically operates on a timescale of a few hours.

Since the open magnetic field lines have one end anchored in the Earth's ionosphere, the motion of the magnetic field lines from the dayside to the nightside and its return to the dayside at lower latitude also creates a two-cell circulation pattern of plasma in the northern and southern hemispheres.

The Dungey cycle transfers energy from the solar wind and IMF into the Earth's magnetosphere, powering the most dynamic phenomena in the magnetosphere, such as auroral processes, atmospheric heating, ground-induced currents and the trapped particle radiation belts. The auroral oval maps predominantly towards the poleward edge of the closed field region. The high-latitude open field region maps to the region within the auroral oval.

The IMF is directed northwards as often as southwards. In 1963, Dungey proposed that low-latitude dayside reconnection could not occur during northward IMF as the field lines were not anti-parallel (Dungey 1963). However, at high latitudes, the IMF and Earth's magnetic fields now become anti-parallel, allowing reconnection there. Magnetic tension drives the newly reconnected field lines sunward at high latitudes and anti-sunward at lower latitudes, producing a two-cell 'lobe convection' pattern, opposite in sense to that under southward IMF. A high-latitude auroral cusp spot forms poleward of the main oval and shifts with the IMF B_y component, allowing direct magnetosheath plasma entry into the ionosphere.

The solar wind and IMF shape Earth's magnetic environment into a 'bullet-shaped' magnetosphere. The outer boundary, where the solar wind is deflected, is called the 'magnetopause', and is maintained by the Chapman-Ferraro currents. Surrounding the planet is the 'ionosphere' – the ionised upper atmosphere extending from roughly 60 to 600km altitude – within which the northern auroral oval occurs. In the inner magnetosphere, the azimuthal ring current flows around the equatorial region. Further out, the middle magnetosphere contains the plasma sheet, a region of high-density plasma and closed magnetic field lines lying between the northern and southern tail lobes. The plasma sheet is bounded by current layers separating it from the lobes, which consist of open magnetic field lines and low-density plasma. These lobes act as reservoirs of magnetic energy during the substorm cycle.

Plasma flows in the two-cell ionospheric convection pattern are associated with horizontal electric fields that drive Pedersen and Hall currents in the E-region ionosphere (~100–130km). The Hall currents flow around the plasma streamlines, opposite to the plasma drift, and in the case of uniform conductivity could, in principle, close entirely within the ionosphere. The Pedersen currents, by contrast, flow perpendicular to the streamlines in the direction of the electric field and close primarily via field-aligned currents (FACs) linking the ionosphere to the magnetosphere. These FACs provide the connection that enables solar wind energy transfer into the magnetosphere-ionosphere system, as first identified by Iijima & Potemra (1976).

The large-scale FACs are organised into Region 1 and Region 2 systems. Region 1 FACs connect the high-latitude ionosphere to the outer magnetosphere, flowing downward on the dusk side and upward on the dawn side, while Region 2 FACs link the ionosphere to the inner magnetosphere, flowing upward on the dusk side and downward on the dawn side. Together, the Pedersen and Hall currents provide the ionospheric closure of these systems. Magnetic perturbations measured on the ground are dominated by the Hall currents, whereas in space they are primarily associated with the Pedersen currents and the connected FACs.

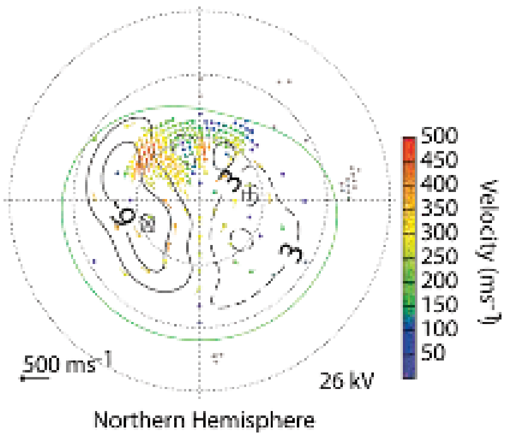
Dungey (1961) proposed that dayside and nightside reconnection occur steadily. However, it later became clear that these processes are highly dynamic, and the magnetospheric response to solar wind forcing is not steady-state. Akasofu (1964) observed that the auroral oval varies significantly in brightness and size. This led, over time, to the development of the magnetospheric substorm cycle.

The substorm cycle consists of three main phases: the growth, expansion and recovery phases. The substorm growth phase, typically lasting 30–60 minutes, occurs when southward IMF enhances dayside reconnection, creating open flux and expanding the auroral oval. Energy is transferred into the magnetotail, where the plasma sheet thins as magnetic flux builds up in the lobes. When the tail becomes unstable, the expansion phase begins with near-Earth reconnection (~20–30 Earth radii away), rapidly releasing stored energy. This drives bright auroral displays and a poleward expansion of the oval as closed field lines move earthward. Ion and electron injections enhance the ring current and radiation belts. After 30–60 minutes, the recovery phase begins, lasting 1–2 hours. The aurorae retreat, plasma flows weaken, and the magnetosphere gradually returns to a more dipolar, stable state.

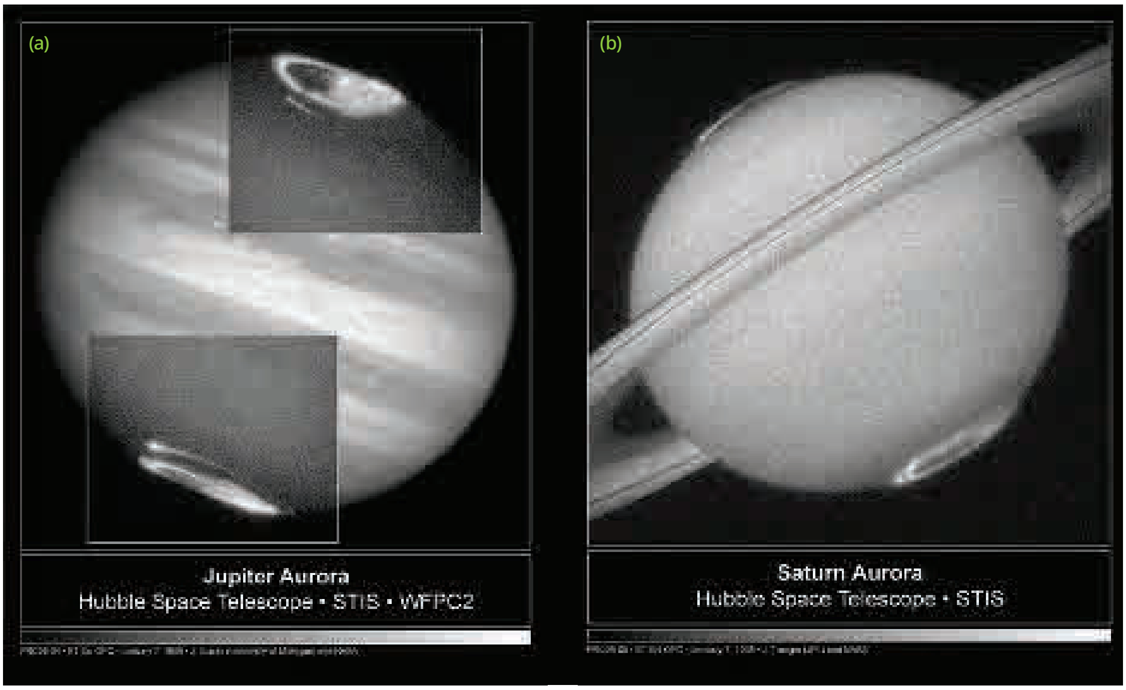
The SuperDARN array of HF radars measures line-of-sight ionospheric plasma motion in the northern and southern polar regions. By combining data from multiple radars, global maps of ionospheric convection can be constructed. For southward IMF, a clear two-cell convection pattern is seen, with anti-sunward flow over the polar cap and sunward return flow at lower latitudes. For northward IMF the radars observe a four-cell convection pattern, with sunward flow over the polar cap and anti-sunward flow at lower latitudes (figure 3).

'Space weather' refers to changing conditions in near-Earth space caused by solar activity and its interaction with Earth's magnetic field and atmosphere. It includes phenomena like geomagnetic storms, solar flares,

"Dungey proposed that dayside and nightside reconnection occur steadily. However, it became clear that these processes are highly dynamic"



3 SuperDARN northern hemisphere convection map during an interval of southward IMF (Liu *et al.* (2015))



4(a) Jupiter overlaid with Jupiter's aurora observed by the HST. (John Clarke (University of Michigan)/NASA) **(b) HST image of Saturn's aurorae.** (JT Trauger (JPL)/NASA)

and energetic particle precipitation, which can affect satellites, power grids, GPS, and communications. Magnetospheric storms drive electric currents, magnetic field fluctuations and high-energy particle influx. Rapid variations in the Earth's magnetic field can result in geomagnetically-induced currents (GICs) which can affect electrical conductors such as the electric grid and oil pipelines. Precipitation of high-energy particles can affect spacecraft, GPS communication and astronauts. As society depends more on space-based systems, accurate space weather monitoring, forecasting, and mitigation are increasingly vital.

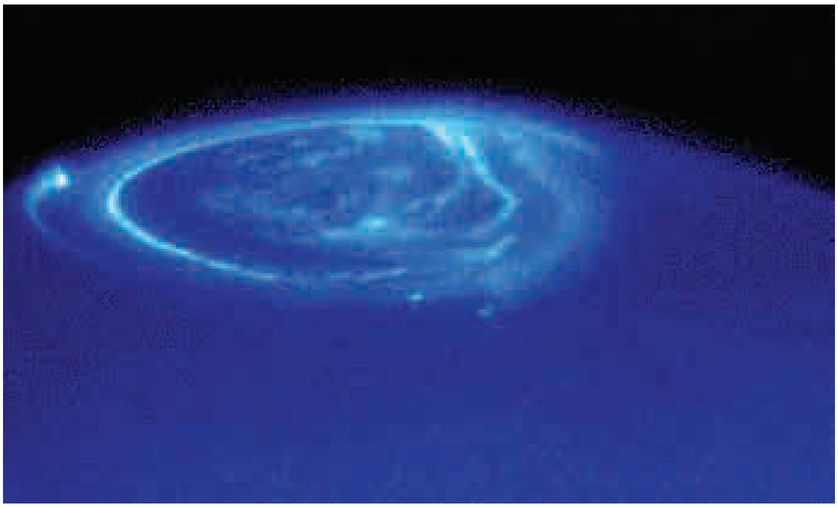
Jupiter's aurorae

Auroral processes throughout the solar system are studied using ground-based observatories (e.g. Keck, VLT, IRTF), space telescopes (e.g. HST, JWST), and spacecraft (e.g. Juno at Jupiter, Cassini at Saturn). Auroral processes occur on any planet or moon with a thick, collisional atmosphere and a magnetic field strong enough to deflect the solar wind or planetary plasma flow. This includes Earth, Jupiter, Saturn, Uranus and Neptune. Mars, which once had a global magnetic field, shows aurorae linked to crustal magnetic remnants (Brain *et al.* 2006). Mercury's weak field produces X-ray and UV aurorae via electron precipitation into its exosphere (Lindsay *et al.* 2016). Venus lacks a magnetic field but shows diffuse UV emissions from solar wind-atmosphere interactions (Gérard *et al.* 2011).

Jupiter possesses the largest and most powerful magnetic environment in the solar system (figure 4a). Its immense magnetic field, with a magnetic moment about 20000 times stronger than Earth's, is generated by the planet's rapid roughly 10-hour rotation and a core of metallic hydrogen. This drives a vast, dynamic magnetosphere that produces aurorae up to ten times brighter than those on Earth. Two key differences distinguish Jupiter's aurorae from Earth's. First, Jupiter's magnetosphere is dominated by the planet's rapid rotation, whereas Earth's is shaped primarily by the solar wind. Second, the plasma sources that power the systems differ. Earth's magnetosphere is driven externally by the solar wind and ionosphere, while Jupiter's is supplied internally, most notably by its volcanic moon Io. Io injects around 1000kg/s of sulphur and oxygen into Jupiter's magnetosphere (Bagenal 1997), forming a dense plasma torus. Confined equatorially by centrifugal forces, this plasma nearly corotates with the planet. As Io moves through Jupiter's magnetic field, it generates a potential of up to 400000 volts and currents of around three million amperes. FACs connect Io to Jupiter's upper atmosphere, producing intense auroral emissions at Io's magnetic footprint in both hemispheres.

Figure 5 is an iconic UV image of Jupiter's aurorae, captured by the HST, revealing several distinct regions. At higher latitudes, emissions linked to moon–magnetosphere interactions are visible. The bright main oval, mapping to the middle magnetosphere, dominates the auroral power output, while the polar cap shows variable, structured 'swirl' aurora.

Cowley & Bunce (2001) modelled how the diffusion of Io's plasma away from Jupiter could generate large FACs which can drive Jupiter's main auroral oval. As the plasma diffuses outwards, its angular velocity starts to fall due to conservation of angular momentum, and the plasma starts to sub-corotate with respect to the planet. Jupiter's magnetic field lines are bent out of the meridional plane into a lagging configuration, observed as a deflection in the B_Φ (azimuthal) component of the magnetic field.



5 UV image of Jupiter's aurorae captured by the HST. (NASA, ESA, John Clarke (University of Michigan))

In Jupiter's ionosphere a differential velocity is created between the neutral particles rotating with the planet and the charged particles rotating with the flux tubes. An ionospheric torque is created which is communicated to the magnetosphere via FACs moving along the magnetic field lines. The inner FACs are directed outwards (upwards) from the ionosphere to the magnetosphere where the angular velocity begins to depart from corotation. These upward FACs are associated with electrons propagating downwards into the ionosphere creating Jupiter's main auroral oval. At higher latitudes, the FACs are directed inwards from the magnetosphere towards the ionosphere, resulting in downward FACs into the polar cap. In both hemispheres, ionospheric Pedersen current flows in an equatorward direction, and close as outward radial currents in the plasma sheet.

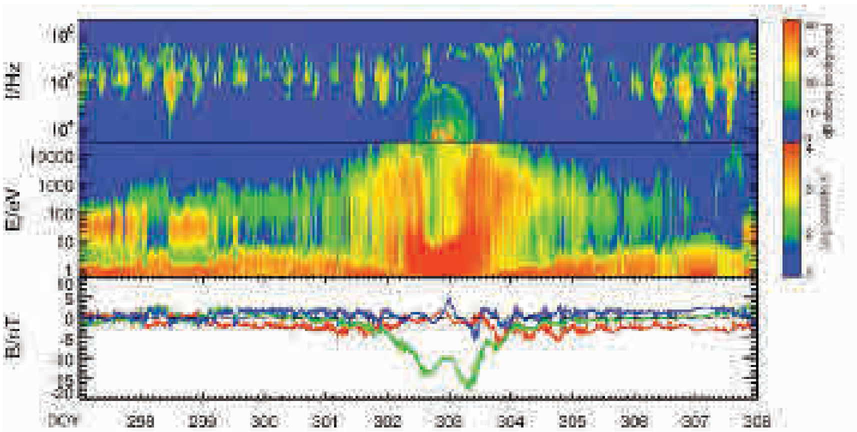
Kotsiaros *et al.* (2019) provided the first evidence from the Juno spacecraft of Jupiter's FACs. Since 2016, Juno has been orbiting Jupiter, passing over both poles every 53 days during its main phase. Kotsiaros *et al.* (2019) presented UV auroral mosaics from the first 11 perijoves. Strong B_Φ deflections aligned with the main auroral emissions revealed the presence of FACs, as expected.

Nichols *et al.* (2020) reported a significant brightening of Jupiter's dawn-side aurora as observed by the HST, coinciding with enhancements in the azimuthal and radial magnetic fields and plasma temperature as observed by Juno. This provided the first evidence that magnetosphere-ionosphere coupling currents control the main auroral intensity. Unsure if a solar wind compression occurred, their modelling suggested the brightening was driven by increased hot plasma temperature and iogenic mass outflow.

Saturn's aurorae

Saturn was orbited by the Cassini spacecraft from 2004 to 2016, a mission I had the pleasure to be associated with for many years and which offered a rich treasure trove of results. Saturn's aurorae look similar to Earth's (figure 4b). As at Jupiter, Saturn's rapid rotation and internal plasma sources play a key role in shaping its aurorae. However, Saturn's plasma source, primarily from the icy moons (especially Enceladus, see Dougherty *et al.* 2006) and ring grains, is estimated to be about ten times weaker than Jupiter's. While sufficient to drive significant sub-corotation of equatorial magnetospheric plasma, Cowley & Bunce (2003) argued that the associated upward FACs are too weak and occur at too low latitudes to produce the main auroral oval. Instead, Cowley *et al.* (2004) proposed that Saturn's main aurorae originate from a ring of upward current at the open-closed field line boundary, driven by shear between the angular velocities of open and outer closed field lines.

Cowley *et al.* (2004) proposed that Saturn's FACs are strongly influenced by solar wind dynamic pressure, with reconnection favoured during northward IMF due to the opposite polarity of the planetary magnetic field compared with Earth. Cowley *et al.* (2005) analysed southern aurorae observed by HST while Cassini monitored the upstream solar wind. They proposed that auroral effects are produced by compression-induced reconnection closing a significant fraction of the open flux present in Saturn's open tail lobes, followed by sub-corotation of the newly closed flux tubes in the outer magnetosphere region due to the action of the ionospheric torque.



6 **Data from Perijove 17 of Cassini at Saturn. The top panel shows data from RPWS showing pulsing of Saturn kilometric radiation (SKR). The second panel present electron density data from CAPS/ELS. The bottom panel presents magnetic field data.** (Gérard *et al.* (2006))

Planetary Period Oscillations (PPOs), rotating close to Saturn's rotation period, are observed throughout Saturn's magnetosphere. They were first observed within Saturn kilometric radiation (SKR), and subsequently in all observable magnetospheric and ionospheric parameters such as the magnetospheric magnetic field, hot and cold plasma populations, narrowband radio emissions, auroral oval position, emitted power, magnetopause and bow shock location, and ionospheric plasma density. Figure 6 (Gérard *et al.* 2006) presents data from Cassini PJ 17, showing the PPOs within Saturn's SKR emission (top panel), electron flux data (middle panel), and magnetic field (bottom panel). Their source is by no means obvious as Saturn's internally generated field is closely axisymmetric, the magnetic axis being aligned with the spin axis to better than 0.01° (Dougherty *et al.* 2018).

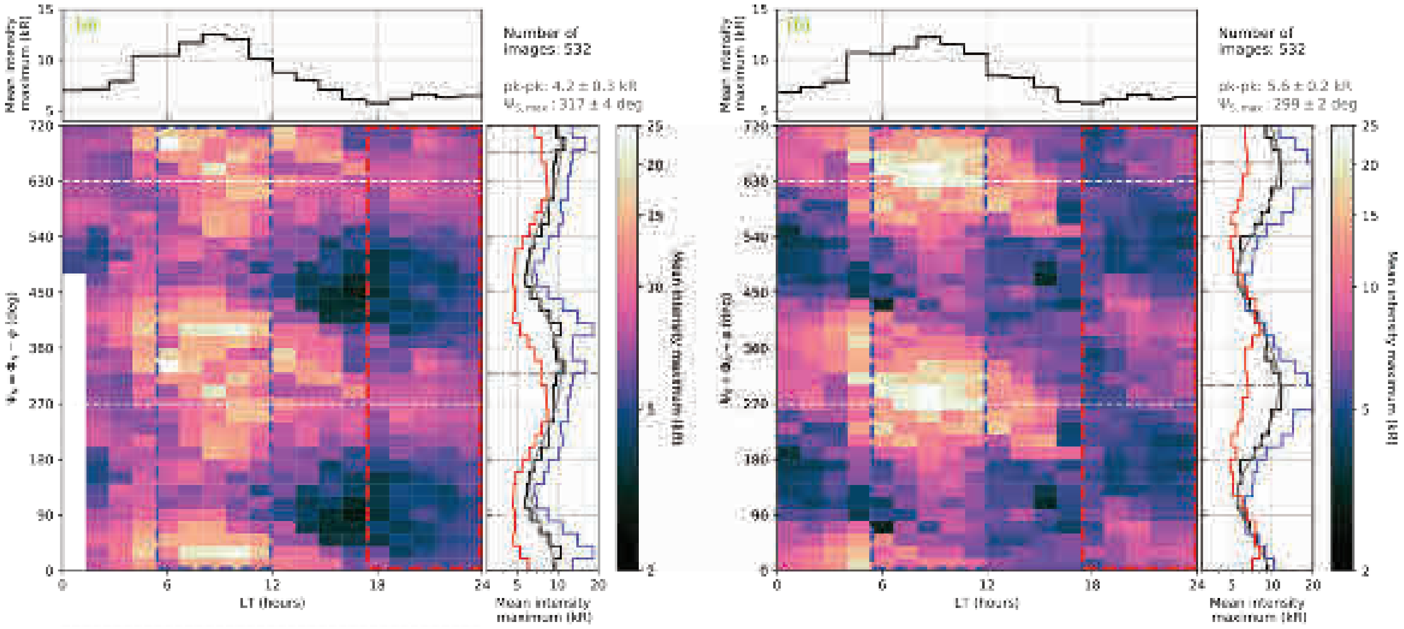
PPOs were first identified in SKR data by Gurnett *et al.* (2009). Two PPO systems exist, one in each hemisphere, with amplitudes, periods and relative amplitudes varying seasonally. Gurnett *et al.* (2009) reported that in 2008, during Saturn's southern hemisphere summer, the southern rotation rate was ~10.81 h and the northern ~10.59 h.

Provan *et al.* (2009) and Andrews *et al.* (2010) examined the polarisation of northern and southern PPO magnetic perturbations at Saturn. These take the form of two rotating magnetic perturbation loops, one per hemisphere, with B_r and B_θ in anti-phase in the north and in phase in the south. The PPO perturbation loops rotate anticlockwise in the same sense as planetary rotation at their respective PPO periods. In the polar regions, the perturbations resemble rotating transverse dipoles. Provan *et al.* (2019) and references therein defined northern and southern magnetic 'local phase' systems based on the dipole pointing direction. These 'local phase' systems are akin to two Saturnian longitude systems, with $\Psi_{N/S} = 0°$ defined where the N/S dipole points away from Saturn. At N/S SKR maxima $\Psi_N = 0°/\Psi_S = 180°$ point towards the Sun.

Hunt *et al.* (2014) presented the southern hemisphere meridional currents as a function of southern PPO phase. The currents were determined from the B_ϕ component of Saturn's magnetic field, observed by Cassini on Revs 59–95, when the spacecraft traversed the southern polar regions. The results clearly show the strongest upward southern PPO current at $\Psi_S = 270°$, and the strongest downward southern current at $\Psi_S = 90°$.

Bader *et al.* (2018) performed a statistical analysis of Saturn's UV auroral emission using all suitable *Cassini*-UVIS images acquired between 2007 and 2017. The FACs associated with plasma sub-corotation at the open-closed

"As at Jupiter, Saturn's rapid rotation and internal plasma sources play a key role in shaping its aurorae"



7 The mean northern hemisphere (a) and southern hemisphere (b) UV auroral intensity as a function of local time and northern (a) and southern (b) PPO phase. Credit: Bader *et al.* (2018).

field-line boundary and the PPO FACs flow together in a narrow region of ionospheric co-latitude and are jointly responsible for creating Saturn's main auroral oval. The northern (southern) aurorae are primarily modulated by northern (southern) PPO phase. Additionally, the Saturnian aurorae can be modulated by the solar wind, and by PPO modulations from the opposite hemisphere. Figure 7 shows the mean intensity of Saturn's northern (figure 7a) and southern (figure 7b) UV aurorae as a function of local time and PPO phase. The brightest aurorae are observed in the northern (southern) hemisphere dawn region at $\Psi_N \sim 90°$ ($\Psi_S \sim 270°$).

PPOs modify Saturn's entire magnetosphere, including the tail current sheet. Maximum plasma sheet thickening/thinning occurs when PPOs are in anti-phase, and maximum vertical displacement when they are in phase. From the above discussion we know that tail reconnection is most likely to occur then the tail plasma sheet is thinned and threaded by the weakest normal field. Thus, PPO modulation of the plasma sheet results in planetary period modulated down-tail mass loss via the Vasyliunas cycle.

Hunt *et al.* (2014) first proved that the PPOs were driven from the atmosphere, based on magnetic field observations. This was later confirmed in a unique study by Chowdhury *et al.* (2022) who presented ground-based Keck-NIRSPEC observations of Saturnian northern hemisphere infrared auroral emission from H_3^+ ions. They demonstrated that the thermosphere/ionosphere moves across the polar cap from $\Psi_N = 180°$ to $\Psi_N = 0°$, evidencing that the PPOs are driven from the atmosphere.

Summary

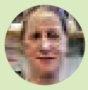
Dungey's original paradigm helped explain Earth's solar wind-driven geospace environment. However, its underlying principle of magnetic reconnection, magnetosphere-ionosphere coupling, and plasma circulation continue to shape our understanding of aurorae both within our solar system and beyond. At Jupiter and Saturn, aurorae are driven not by direct solar wind driving, but by both internal and external processes. At Saturn in particular, growing evidence suggests that the upper atmosphere and ionosphere may play an active role in driving magnetospheric dynamics, blurring the traditional distinction between 'external' and 'internal' forcing. These systems challenge us to extend Dungey's ideas, not abandon them, demonstrating how a framework rooted in reconnection and global circulation can be adapted to regimes where internal plasma sources and atmospheric feedbacks are central.

Looking ahead, the next phase of auroral research lies in fully embracing this coupled system-level view. Advances in multi-wavelength observations from facilities such as HST and JWST, combined with *in situ* measurements from missions like Juno and future outer-planet explorers, are allowing us to trace energy and momentum flow continuously from the solar wind, through the magnetosphere, and down into planetary atmospheres. At Jupiter, continued analysis of the Juno dataset has recently resulted in determination of nightside ionospheric FACs and conductivities. In doing so, we are increasingly recognising aurorae as a diagnostic – and driver – of whole-system behaviour rather than a passive by-product of space weather.

This perspective is perhaps Dungey's most enduring legacy: the insistence that magnetospheres must be understood as dynamic, interconnected systems governed by global electrodynamics, continuing to guide how we ask questions about planetary space environments and their interaction with stars. ●

ACKNOWLEDGEMENTS
The author would like to dedicate this article to the memory of a dear friend, Professor Kathryn McWilliams, RAS Honorary Fellow.

AUTHOR
Gabby Provan (University of Leicester) is of Norwegian-Scottish descent. Her research focuses on large-scale magnetic field interactions in solar-system magnetospheres, including solar wind–planet interactions and magnetosphere–ionosphere coupling.



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Solar influences on Earth: past, present and future

(Fer Troulik/Unsplash/NASA/Goddard/SDO/J Hannah)

In his President's Address, given in May 2026, **Mike Lockwood** explores how our understanding of the Sun's influence on Earth has evolved, and how studies of exoplanets promise to place it in a wider astrophysical context

Understanding how the Sun influences Earth has been a central theme in space and climate science for over a century. In this article, I review how our understanding of Sun-Earth connections has developed, what current research reveals about these processes, and how studies of exoplanetary systems may help to place the Sun and Earth in a broader astrophysical context.

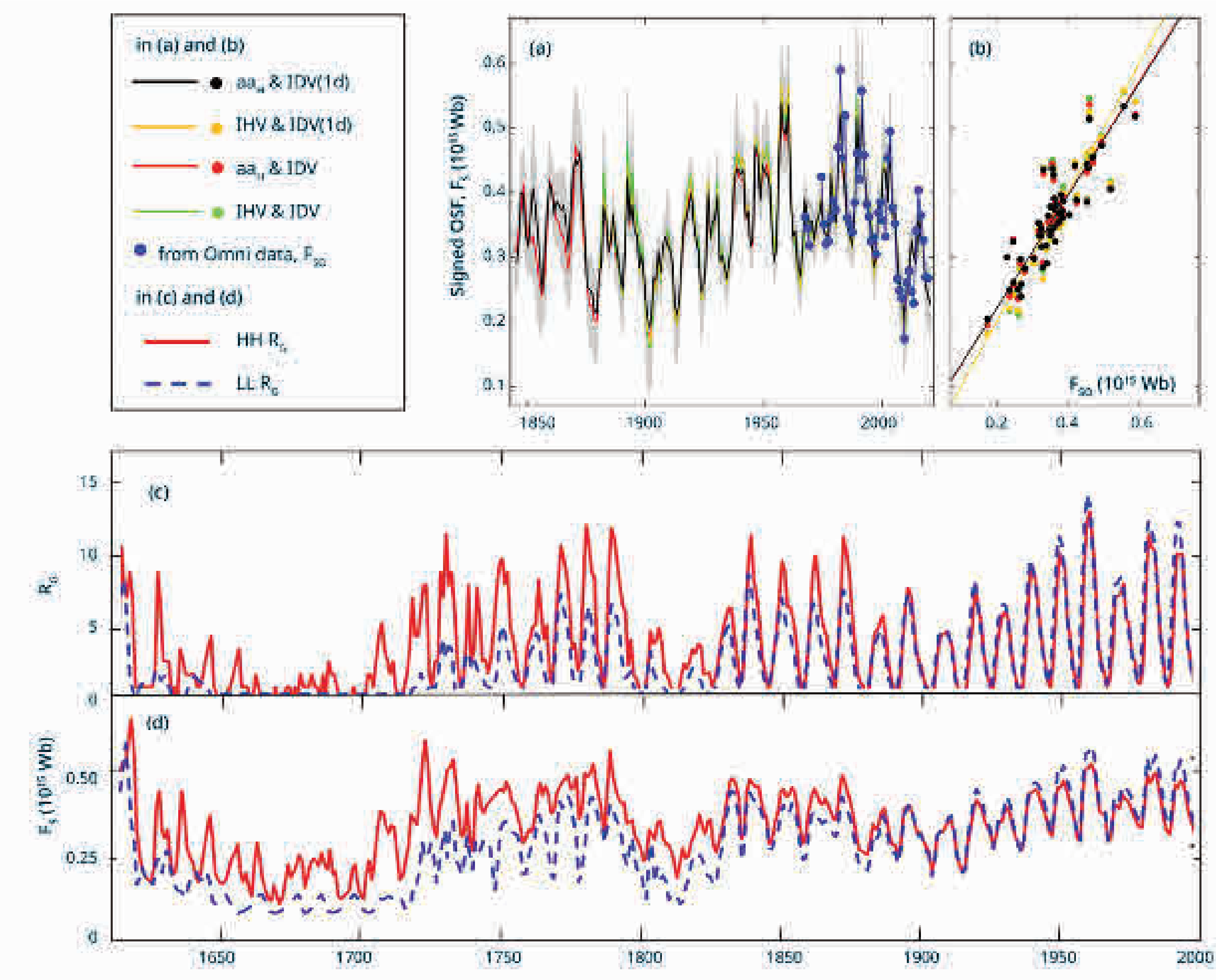
Past

Reconstructing past fluctuations in the Sun's influence on Earth is an area that I stumbled into, as member of a grant review panel. It is an example that I give to young researchers of the benefits to one's own science of contributing to peer review. On that panel, I was introduced to the *aa* geomagnetic index that was initially compiled for 1868–1968 by Jesuit priest Father Pierre-Noël Mayaud. It is now continued to the present day, covering over 157 years. My interest was sparked by the long-term variation revealed by *aa*. A literature search soon showed that Feynman & Crooker (1978) had made a serious attempt to exploit the longevity of the index.

They had used the correlation between *aa* and the product $B_sV_{sw}^2$, where B_s is the southward component of the interplanetary magnetic field, IMF $\underline{\mathbf{B}}$, in the geocentric solar magnetospheric frame, and V_{sw} is the solar wind speed. This correlation is understood because B_s facilitates power extraction from the solar wind through magnetic reconnection with the geomagnetic field, and the V_{sw}^2 term arises because the dominant energy in interplanetary space is the kinetic energy of the solar wind particles.

Feynman & Crooker examined how V_{sw} must have varied to explain the *aa* index variation if B_s was assumed constant. They were aware that this assumption was of limited validity. We devised a way to eliminate the assumption (Lockwood *et al.* 1999), using the fact that solar wind speed variations cause geomagnetic disturbances that recur every solar rotation (≈27 days), so the autocorrelation of *aa* at this period correlates very well with V_{sw}. In addition, we realised that although *aa* correlates strongly with B_s on short timescales, when averaged over a year, the IMF orientation factor B_s/B is essentially constant.

Through Parker spiral theory of the IMF, the ratio B_r/B could be computed, where B_r is the radial component of the IMF away from the Sun. Hence, we were able to compute the long-term variation in annual means of B_r from the *aa* data. However, B_r is a local parameter of the near-Earth heliosphere, and we were interested in a global solar parameter. The final piece of the jigsaw was the realisation that taking annual means averaged out the heliographic longitudinal structure in $|B_r|$, and that the Ulysses spacecraft had recently observed that $|B_r|$ was independent of heliographic latitude.



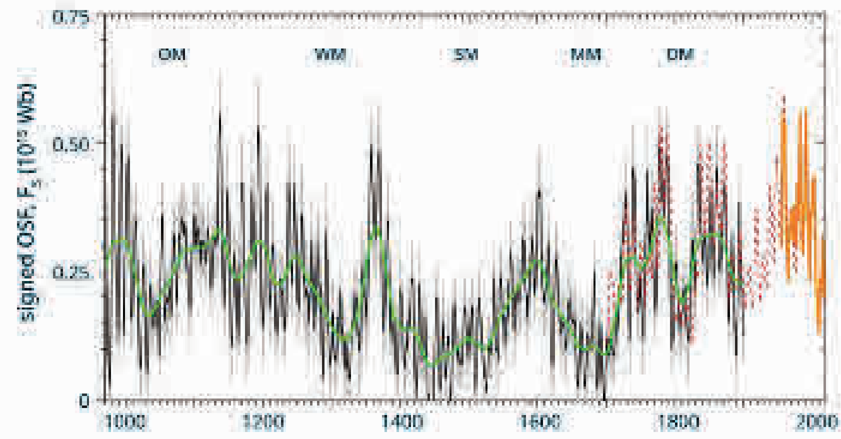
1 Reconstructions (Lockwood *et al.* 2022) of annual means of the signed OSF, F_S. (a) shows the reconstructions from four combinations of geomagnetic indices, using spacecraft observations F_{SO} from near-Earth interplanetary space, with correction for heliospheric 'switchbacks' (blue dots). (b) shows the relationships between the F_S and F_{SO} estimates. (d) shows these reconstructions extended back to 1600 using the cosmogenic isotope ^{44}Ti measured in meteorites (Asvestari *et al.* 2017). This reconstruction is made using the continuity equation for F_S, quantifying the source term using the HH and LL group sunspot number variations, R_G, shown in (c).

This empirical result is readily understood because close to the Sun the plasma β – the ratio of plasma to magnetic pressure – is small and magnetic pressure dominates. This means slightly non-radial flows equalise the tangential magnetic pressure, rendering the modulus of the radial field $|B_r|$ constant. Hence, our local B_r averages allowed us to compute the total signed solar magnetic flux threading a heliocentric sphere of radius $R_\oplus$ = 1 au, as $4\pi R_\oplus^2 <|B_r|>/2$. This was initially taken as an estimate of the signed open solar flux (OSF) leaving the top of the solar atmosphere and entering the heliosphere.

A lot of work was then undertaken to refine this result. There was considerable debate about the veracity of the drift in *aa*, largely due to misunderstandings of the method Mayaud (1972) had used in its compilation. This was definitively resolved by Lockwood *et al.* (2018), who used models of the intrinsic geomagnetic field to correct for the drift in magnetic latitude of each station before intercalibrating daily means as a function of time of year. This method resulted in aa_H, which unlike *aa*, has almost identical but independent variations from northern and southern hemisphere stations. Both *aa* and aa_H are 'range' indices, based on the range of variation in the horizontal field observed at a station over three-hour intervals. Other long-sequence geomagnetic activity indices, namely *IHV*, *IDV* and *IDV*(1d), have now been developed using hourly averages. They respond differently to solar wind and IMF conditions, a property that we can exploit.

Another complication is that, although $4\pi R_\oplus^2 <|B_r|>/2$ is the signed flux threading a surface at the heliocentric distance r = $R_\oplus$, this exceeds the OSF, F_S, defined as the unsigned flux threading the 'coronal source surface' at the top of the solar corona. This is because field lines between the two can fold back on themselves – a phenomenon that has received much recent attention as 'switchbacks' in data from the Parker Solar Probe. After a variety of approximate corrections for the 'excess flux' this causes, a method was devised by Owens *et al.* (2017) and implemented by Frost *et al.* (2022). This method uses the fact that the hot corona generates a stream of 'strahl' electrons that always flow away from the Sun along magnetic field lines, so if the field lines are folded back on themselves, they are detected as strahl moving back towards the Sun. Thus, the amount of folded flux can be computed and the OSF accurately evaluated.

A further improvement was the realisation that, instead



2 **The signed OSF, F_S, deduced from ^{14}C deposited in trees is shown (black), with the uncertainty band (grey) and smoothed running means (green). The reconstruction is calibrated from spacecraft data (orange, as shown in figure 1) and extended through modelled values from sunspot numbers fitted to geomagnetic data (dashed red line). From Usoskin (2023).**

of using the 27-day autocorrelation in *aa* to account for V_{sw}, a better method was to use different geomagnetic activity indices. In general, annual means of geomagnetic indices depend on BV_{sw}^n, where n = 1.76 for aa_H, slightly lower than the value of 2 initially found for *aa*, 1.68 for *IHV*, and –0.08 for *IDV*(1d) and –0.05 for *IDV*. Hence, by using combinations of indices for which n differs significantly, the variations in B, V_{sw} and F_S can all be computed. The result of these improvements can be seen in the review by Lockwood *et al.* (2022). The strong similarity of reconstructions from the four different combinations of geomagnetic indices with significantly different n is shown in figure 1(a), while figure 1(b) shows that they all agree well with the annual means of OSF derived from spacecraft data, F_{SO}, including the correction for folded field lines, as indicated by the blue dots in figure 1(a).

Hence, using historic geomagnetic data, together with understanding from space-age data extending back only to 1964, we have been able to reconstruct annual means of interplanetary parameters back to 1844. Recent work has increased the time resolution by over an order of magnitude by deriving means for each Carrington rotation of the Sun (Lockwood & Owens 2024).

"The ^{14}C record from trees can be used up until about 1950, when ^{14}C from atomic bomb tests swamped the record"

The more distant past

Using cosmogenic isotope abundances found in dateable terrestrial reservoirs, we can go back further in time. Beryllium-10 (^{10}Be), Carbon-14 (^{14}C) and Chlorine-36 (^{36}Cl) are generated as spallation or neutron-capture products of galactic cosmic rays (GCRs) striking atoms in our atmosphere. They inform us about OSF because the magnetic field in the heliosphere shields Earth from cosmic rays. Hence, the greater the OSF, the lower the abundances of cosmogenic isotopes. For long timescales, we must also account for changes in the geomagnetic field, as this also shields our atmosphere from GCRs (Usoskin 2023).

The ^{10}Be cosmogenic isotope is produced when GCRs with a broad range of energies impact atmospheric atoms. It is then attached to aerosols and precipitates into ice sheets, sediments and soils. It takes several weeks for ^{10}Be produced in the troposphere to be deposited, and about two years for ^{10}Be made in the stratosphere. Most ^{10}Be is deposited in polar ice sheets about a year after production. We cannot make reliable measurements of ^{10}Be abundances in 'firn', the intermediate state between fresh snow and compacted ice, but otherwise dateable ^{10}Be abundances can be determined from ice cores until relatively recent times.

^{14}C is different because carbon is exchanged between the atmosphere, the oceans and biomass in the carbon cycle. Trees incorporate atmospheric CO_2, including cosmogenic ^{14}C, during photosynthesis in the growing season; deposition in this reservoir then occurs 1–2 years after production and is smoothed over several years. Abundances can be determined from cores taken from ancient trees and from wood in historical buildings. The abundances must be analysed using a model that accounts for the carbon cycle if the production rate is to be determined (Zhang *et al.* 2022). The ^{14}C record from trees can be used up until about 1950, when ^{14}C from atomic bomb tests swamped the record.

Abundances of ^{36}Cl are lower, and there are competing production sources and chemical complications. It takes two years on average to be deposited because it is mostly formed in the stratosphere. These factors mean that ^{36}Cl data have lower time resolution than the annual resolution achievable with ^{14}C and ^{10}Be; however, it is most sensitive to lower-energy protons in the range 30–100 MeV, which helps to identify a solar, as opposed to galactic, origin of the causal particles. Like ^{14}C, ^{36}Cl is usable up to about 1950.

Figure 1(c) shows two reconstructions of the group sunspot number, R_G, labelled HH and LL and shown by red solid and blue dashed lines, respectively. These sequences differ before about 1820 because of uncertainties in intercalibrating observations from different observers. Using these R_G data, the highly successful continuity model of Solanki *et al.* (2000) is applied to compute the OSF. Figure 1(d) shows the resulting signed OSF computed from cosmogenic Titanium-44 (^{44}Ti) by Asvestari et al. (2017). Its ~60-yr half-life means that it formed on a meteorite during the final part of its journey to Earth, but the fall date must be known to allow for continuing decay on the ground. The Maunder Minimum (c1670–1710) can be seen in both OSF reconstructions, but it is deeper for the LL reconstruction. Reconstructions using ^{10}Be and/or ^{14}C can extend further back in time. Figure 2 shows a reconstruction extending back to 1000 CE, in which the Maunder Minimum is one of a sequence of grand minima, following the Oort (OM), Wolf (WM), and Spörer (SM) minima. The subsequent, shorter-lived Dalton Minimum (DM) is also labelled.

Reconstructions are possible back to about 7000 BCE, but these cosmogenic isotope data contain surprises. The biggest was discovered by Japanese PhD student Fusa Miyake, who found an event that occurred in 774 CE (Miyake 2012). Subsequently, similar confirmed spikes have been detected in dated records for 7176 BCE, 5259 BCE, 664–663 BCE and 993 CE. In addition, candidate events awaiting full confirmation have been identified for 12350 BCE, 5410 BCE, 1052 CE and 1279 CE.

What is astonishing about these events is the flux of energetic particles required to generate such large cosmogenic isotope abundances. The annual tree-ring record for the 774 CE event shows a ^{14}C increase of about 12 ppm, corresponding to a 1.2% increase in global atmospheric ^{14}C. This is roughly 20 times larger than the normal year-to-year variability, and the estimated global ^{14}C production during the event is approximately three to four times the normal annual production. Note that the carbon cycle reduces the ^{14}C signal and spreads it over subsequent years (Zhang *et al.* 2022).

Several non-solar mechanisms have been proposed, including supernovae, gamma-ray bursts, comet impacts, comet debris deposition, superflares from a nearby magnetar neutron star, and bursts of GCRs from nearby astrophysical accelerators. None of these provide satisfactory explanations. For example, comet theories are very unlikely because the ^{14}C spikes are very similar in ice cores from both poles, and gamma rays are also unlikely because isotope ratios – especially ^{36}Cl/^{10}Be – are better explained by proton-driven production than by gamma-ray cascades (Mekhaldi *et al.* 2015).

The one remaining explanation is extreme solar energetic particle (SEP) events, produced by very large solar flares and probably associated with extreme coronal mass ejections (CME). This scenario matches the observed production of different isotopes. Tree-ring records show a one-year jump, consistent with days of SEP bombardment. The difficulty for this proposed explanation is that the required particle fluence corresponds to an SEP event 30–100 times larger than the largest modern event.

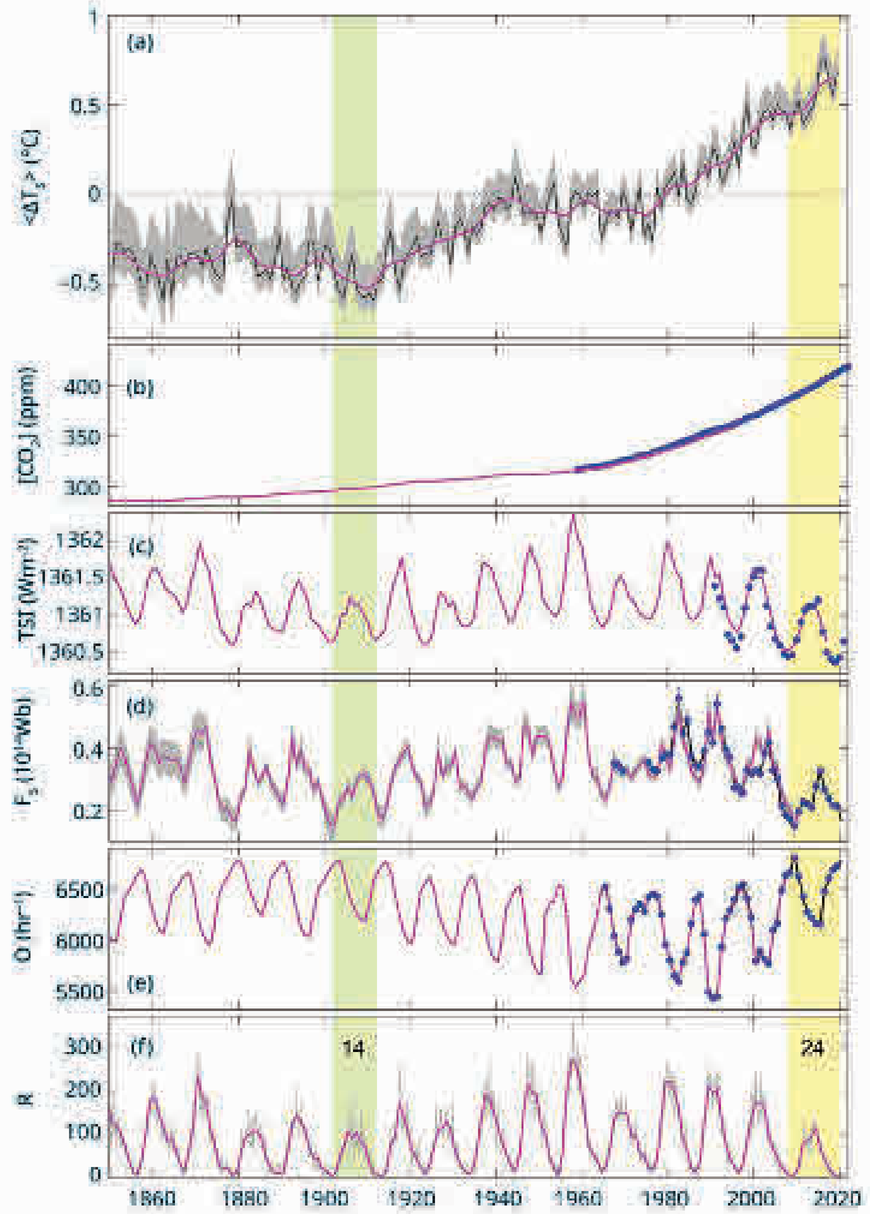
The consensus is that Miyake events are indeed extreme SEP events, far larger than anything observed during the space age. Although very rare, the hazard inherent in these events is very large indeed. A Miyake event would cause widespread malfunctions and loss of spacecraft, degradation of solar panels, damage to electronics and navigation systems, and disruption or loss of weather and communication satellites. Radiation exposure for astronauts on the International Space Station would be severe, and exposure on lunar missions would likely be lethal. High-latitude aircraft would experience large radiation doses for passengers and crew, with polar flights diverted or grounded.

Such an event would not be extinction-level, as the atmosphere and geomagnetic field still provide strong shielding, so surface radiation flux increases would be small. An event of the size observed in 774 CE is estimated to occur roughly once every 1000 years on average.

Present

There are a huge number of ongoing studies on the current state of solar influences on near-Earth space. These include understanding how large solar eruptions form and searching for precursors; probing the inner heliosphere and the origins of the solar wind; forecasting the structures and geoeffectiveness of CMEs; predicting the solar cycle and understanding the solar dynamo; investigating high-energy particle acceleration and their propagation to Earth; examining UT variations in the magnetosphere associated with the eccentric nature of the geomagnetic field; understanding preconditioning of geospace and compounding of events; analysing wave-particle interactions and loss processes in the radiation belts; quantifying the rapid acceleration of relativistic electrons; assessing solar forcing of the middle atmosphere; and determining what triggers magnetospheric substorms, including hemispheric differences. In all these areas, techniques such as ensemble modelling, skill scores, data assimilation, machine learning and AI are increasingly deployed. These are just a few examples of ongoing research that will continue and inform the studies discussed below in relation to exoplanets.

Instead of reviewing these many current activities, this section considers an application of the work described in the previous sections that helps confirm the drivers of the current state of Earth's climate. This debate dates to William Herschel, who identified an anticorrelation between sunspot number and the global market price of grain (Herschel 1801). His argument was that the sunspots decreased the Total Solar Irradiance (TSI) – the power per unit area at a distance 1 au from the Sun – thereby lowering global average temperatures, reducing grain yields and pushing up prices on global markets. There are many issues with this logic. For example, numerous factors influence market prices, and many others



3 Variations in annual means of solar and heliospheric parameters compared with terrestrial climate change parameters. In each panel, the mauve line shows an historical reconstruction and the grey bands its 2-σ uncertainty; blue dots denote modern instrumental observations. Green and yellow vertical bands mark sunspot cycles 14 and 24, respectively. (a) The HadCRUT instrumental GMAST anomaly, relative to the 1980 value (Morice *et al.* 2012); the mauve line shows a 3-point running mean of the annual values (black); (b) Atmospheric carbon dioxide concentration, [CO_2]: the mauve line is from ice cores at Law Dome, Antarctica (Rubino *et al.* 2019) and observations from Mauna Loa, Hawaii (Keeling *et al.* 2009); (c) TSI reconstructed using the SATIRE-T model (Wu *et al.* 2018) and from the PMOD data composite; (d) Signed open solar flux, F_S, reconstructed by Owens & Lockwood (2012) and measured by Frost *et al.* (2022); (e) Cosmic ray flux, O, reconstructed by Usoskin *et al.* (2002) and measured at the Oulu cosmic ray station; (f) Monthly (grey) and annual (mauve) sunspot numbers, R, by Clette *et al.* (2023).

affect grain yields. However, the biggest problem with Herschel's idea is that we now understand that increased sunspot numbers cause a rise, and not a fall, in TSI.

Small changes in TSI arise from magnetic fields threading the solar photosphere. Sunspots are relatively large magnetic flux tubes, with typical diameters 2000–20000km, and the inhibition of upward heat transport by the magnetic field causes the temperature at the spot centre to be 3800–4200 K, compared with about 5770 K for the quiet Sun. As a result, they appear dark. On typical timescales of days to weeks, sunspot flux tubes disperse into smaller ones. Once their diameter falls below about 500 km, they appear as bright faculae, especially near the solar limb. This is because at these small diameters, the temperature in the flux tube is maintained by horizontal heat transport, but the density is lower because of magnetic pressure, allowing us to see deeper into the Sun. Near the solar limb, we observe the denser walls of these small flux tubes, which appear bright. This is often called the 'hot wall effect', although this is a misnomer, as it is the higher density of the flux tube walls that makes them brighter. The number of faculae is correlated with the number of sunspots, but their total area is an order of magnitude greater than that of sunspots. Hence, the brightening effect of faculae dominates over the darkening effect of spots (e.g. figure 1 of Lockwood & Ball 2020). Therefore, higher sunspot numbers cause slightly elevated TSI, rather than the decrease assumed by Herschel.

The claim that solar variability is the origin of climate change is a persistent one. Because the TSI determines the Global Mean Atmospheric Surface Temperature (GMAST) – a standard measure taken 2 m above the ground – people often assume that centennial variations in GMAST are caused by corresponding variations in TSI. However, TSI changes are too small for this to be the case. There is a simple reason for this: the solar convection zone (CZ) contains a mass of ~3×10^{28} kg, giving a thermal timescale of ~10^5 yr. Hence, over 100 yr, at most ~10^{-3} of the CZ thermal energy could be released, giving a fractional solar luminosity change of the same order of magnitude. This yields a maximum climate radiative forcing of about 0.9 W m^{-2}, whereas the increase in greenhouse gas forcing over the same interval is about 2.3 W m^{-2}.

Climate scientists have long understood that solar variability is only a minor contributor to recent global warming compared to anthropogenic greenhouse gases (e.g. Jones *et al.* 2012). This is demonstrated by many detection-attribution studies using climate models, as well as by observational data sets that reveal a global downward trend in stratospheric temperatures while tropospheric temperatures have risen (e.g. Shangguan *et al.* 2019). This is a unique signature of greenhouse heat trapping between the stratosphere and troposphere, and inconsistent with a TSI increase that would have caused heating at all altitudes. Useful confirmation of this conclusion comes from comparing the time series of GMAST with various solar parameters, as shown in figure 3.

The OSF variations shown in figure 1 have been used to reconstruct TSI variations caused by magnetic field effects on the emissivity of the photosphere. The SATIRE suite of models is an evolution of the OSF model of Solanki *et al.* (2000) and integrates the emission from photospheric features at given locations on the solar disc. Figure 3 compares variations in key solar and climate

"The biggest problem with Herschel's idea is that we now understand that increased sunspot numbers cause a rise, and not a fall, in TSI"

parameters. Figure 3(c) shows TSI variations modelled using the SATIRE-T model by Wu *et al.* (2018), compared with values from spacecraft data. It should be noted that the reconstruction is calibrated using the PMOD TSI data composite, shown here by the blue dots only after the 'ACRIM gap' which makes the calibration of earlier data uncertain (see the review by Lockwood & Ball 2020).

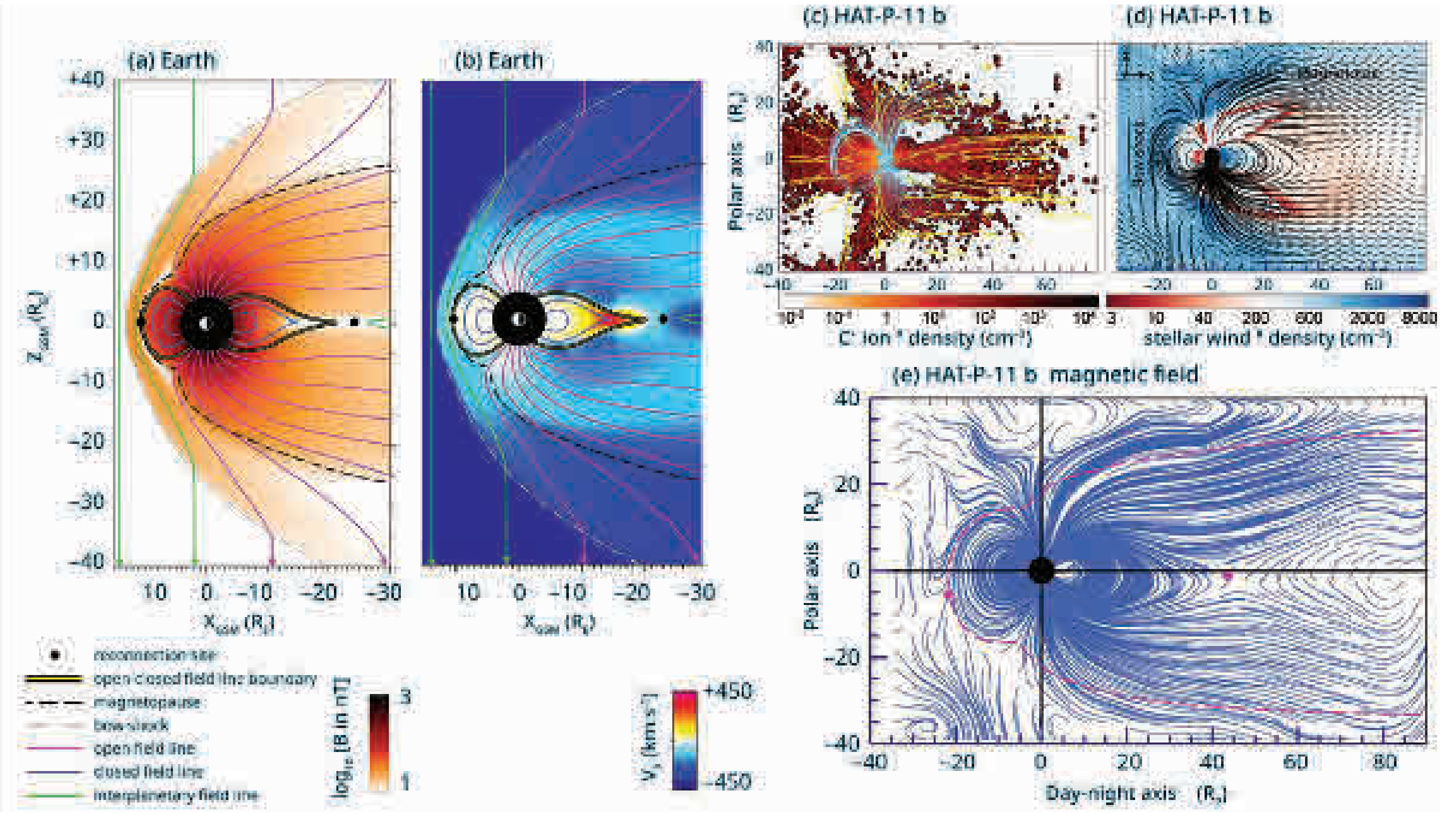
Figure 3 illustrates a point first highlighted by Lockwood & Frölich (2007): the period 1960–80 marked a turning point in solar activity, which had been rising since 1900, but subsequently declined such that by 2020 it had returned to the 1900 level. The grand maximum in long-term running means occurred in 1984 (Lockwood *et al.* 2022). Notably, GMAST rose both before and after the solar grand maximum. The rise in GMAST did pause between 1945–75, which is well understood as the cooling effect of sulphate aerosol pollution (Jones *et al.* 2012). The long-term variation in TSI, OSF and sunspot number are all consistent, and the variation in GCR flux, *O*, shows a strong anticorrelation with OSF.

The fact that the GMAST continued to rise after *O* reached its minimum during the grand solar maximum eliminates the much-discussed hypothesis that the temperature rise is due to GCRs seeding clouds. Clouds do have a major feedback effect on climate: they reflect incoming solar shortwave radiation, influencing Earth's albedo, but also contribute to the greenhouse effect by trapping outgoing longwave radiation and so can both cool and heat the planet. Their effect varies greatly with altitude, but the net effect of clouds is global cooling. Examining figures 2(d) and 2(e), we see that the rise in OSF between 1900 and 1960 reduced GCR fluxes. Hence, if clouds were seeded by GCRs, this would have decreased cloud cover and warmed the Earth. However, after 1990, GCR fluxes clearly rose again, which would be expected to have a cooling effect, yet GMAST values continued to rise.

It is instructive to compare solar cycles 14 and 24, highlighted in figure 3 by the green and yellow bands. In all the solar variations – sunspot number, OSF, TSI and GCR fluxes – these two cycles are very similar, yet figure 3(a) shows that GMAST was roughly one degree higher during cycle 24. The key difference between these cycles is the increase in greenhouse gas mixing ratios. For example, figure 2(b) shows that CO_2 concentrations rose from an average of 285 ppm during cycle 14 to 405 ppm during cycle 24, while analyses of air trapped in ice-sheet bubbles indicate pre-industrial levels were around 280 ppm.

Of course, global means do not reflect conditions at individual locations. Solar UV radiation variability influences the stratosphere, which is only a tiny perturbation to the global energy budget. However, some weather features, such as the jet stream, span the top of the troposphere and the bottom of the stratosphere and can be influenced by solar UV variability, producing regional variability (e.g. Woollings *et al.* 2010).

Like all scientific understanding, our knowledge of climate change can be described as a 'theory' and, as in all areas of science, acceptance of a theory is based on the consensus of scientists who specialise in that field, formed through peer review. Such a consensus is almost never completely universal. That climate change is currently being driven predominantly by anthropogenic activities is as near universal a scientific consensus as has ever been reached. Among those qualified to judge, the level of agreement



4 Application of Dungey's open magnetosphere model to exoplanets. (a) and (b) show global numerical model predictions of Earth's magnetosphere from simulations using the SWMF MHD model (Tóth *et al.* 2012) with a geocentric dipole model of Earth's intrinsic geomagnetic field and zero dipole tilt (from Lockwood 2023). (a) shows the magnetic field, B, on a logarithmic scale, and (b) shows the sunward plasma velocity, V_X. Mauve, blue and green lines indicate open, closed and interplanetary field lines, respectively. Mauve field lines that reach $X = -30R_E$ (where the mean Earth radius $1R_E = 6370$ km) are open because they thread the magnetopause at $X < -30R_E$. (c)–(e) are from analysis of the exoplanet HAT-P-11 b by Ben-Jaffel *et al.* (2022). (c) shows planetary C^+ (CII) ion abundances inferred from HST UV absorption spectra during transits; these ions are seen in the magnetosphere of the exoplanet, escaping from it along open field lines. (d) shows model-inferred magnetic field line segments superposed on a colour-coded plot of derived stellar wind proton number density. (e) shows the modelled magnetosphere of the exoplanet, which exhibits striking similarities to that modelled for the Earth.

is comparable to that for Einstein's theory of general relativity, which has passed every test that astronomers and cosmologists have applied to it. My personal, but firm, belief is that politicians who claim climate science is a 'scientific fraud' should never be granted stewardship of any part of the only habitable planet we know.

"My personal, but firm, belief is that politicians who claim climate science is a 'scientific fraud' should never be granted stewardship of any part of the only habitable planet we know"

Future

I will not attempt to predict the future of solar influences on near-Earth space or climate; however, I will discuss how we might learn more about them from exoplanets. Modelling work is already highlighting ways we could understand how orbit changes drive Milankovitch-cycle climate oscillations between ice ages and interglacials (e.g. Quarles *et al.* 2022).

On timescales of 10^8 years and greater, observations of many Sun-like stars provide insight into how the mass, rotation rate and magnetic field of our Sun will evolve. There have also been studies of how Earth's magnetosphere might respond to the resulting changes in the solar wind (e.g. Carolan *et al.* 2019). This work does not yet account for changes in Earth's magnetic field or for the fluctuations in the solar dynamo that produce grand minima in solar activity.

Looking ahead to millennia, centuries and even decades, we cannot yet predict the evolution of solar activity. At present, the rise and peak of a solar cycle can be predicted quite accurately from the open solar flux during the preceding sunspot minimum. However, in the declining phase of the cycle, unexpected events occur almost at random. During this time, the 'butterfly diagram' shows that sunspots start to appear near the solar equator, and this appears to introduce unpredictability into the second half of the solar cycle and subsequent cycles.

Small eddies and diffusion can move sunspots that emerged in one hemisphere into the other, causing them to evolve in an unexpected way. In addition, magnetic reconnection between emerged loops in opposite hemispheres can generate field-line 'bridges' between the two hemispheres. These seemingly small phenomena appear to have a disproportionate effect on the evolution of the solar magnetic field (Cameron *et al.* 2013; Lockwood *et al.* 2017).

A central limitation in understanding the long-term evolution of the Sun–Earth system is that we possess only a single example, and detailed observations of that example span only recent decades. Prior to this, we have only a few historic observation proxies, cosmogenic isotope records and remanent magnetisation in solidified lava flows. Exoplanets orbiting nearby Sun-like stars provide a natural time series for studying solar evolution (Gonzalez 2025), and magnetised rocky exoplanets offer the possibility of observing stellar wind-magnetosphere interactions across evolutionary sequences.

Figure 4 presents an exciting example: a 'hot-Neptune' exoplanet in close orbit around a K-type star, which is cooler and smaller than our Sun, a G-type star (Ben-Jaffel *et al.* 2022). The paper employs UV absorption spectra measured by the Hubble Space Telescope during planetary transits across the stellar disc, combined with understanding of Earth's magnetosphere, the Dungey cycle, and numerical modelling, to infer the structure of the planet's magnetosphere. It is quite astonishing to think that our model of Earth's magnetosphere has taken a century to develop, with its boundaries just

3×10^{-9} pc away, yet figure 4 provides a plausible depiction of a magnetosphere 38 pc away! Future studies of this type will be possible using the Plato mission, which will combine transit observations with stellar data from a ground-based array of asteroseismology detectors.

A key issue is how many candidate Earth-like exoplanet-stellar wind systems we will be able to observe. Occurrence rate estimates from the Kepler mission indicate that Earth-size planets (≈ 0.8–1.5 $R_{\oplus}$) at roughly Earth-like orbital distances (~ 0.8–1.5 au) around FGK stars occur at a rate $\eta_{(\oplus,1au)} \approx 14\% \pm 11\%$ (Petigura *et al.* 2013; Kunimoto & Matthews 2020). Note that in this section, uncertainty ranges span conservative to optimistic estimates.

The fraction of such planets capable of sustaining a magnetic dynamo is not yet known. Thermal evolution and dynamo-scaling models indicate that rocky planets with masses above about half an Earth mass can plausibly maintain core convection under Earth-like compositions (Driscoll & Olson 2011). This suggests that the dynamo-capable fraction may reduce the sample numbers by at most a factor of two. A reasonable working estimate is that 9% ± 8% of FGK stars host Earth-size planets at ~ 1 au capable of sustaining significant magnetic fields. Within 30 pc of Earth, there are approximately 2000 ± 200 FGK stars, based on modern nearby-star censuses derived from sources such as Gaia (Henry *et al.* 2018). This implies there could be 180 ± 160 nearby candidate Sun-Earth analogue systems for comparative studies of stellar wind-magnetosphere interactions. If we define a grand solar minimum as having an OSF level below 0.23×10^{15} Wb, figure 2 indicates that our Sun has been in such a state for about one-third of the last 950 years. This may be an usually high fraction, but some of these exoplanets are very likely orbiting stars currently in a grand minimum state.

Unlike transit spectroscopy studies, such as that shown in figure 4, which suffer from the low probability of geometric alignment (about $R_\star/a \approx 0.5\%$ for circular ~ 1 au orbits, where $R_\star$ is the stellar radius), radio diagnostics impose no alignment requirement; detectability is therefore limited by instrument sensitivity rather than geometry. Stellar wind mass-loss rates for solar analogues evolve in a known way (Johnstone *et al.* 2015), implying that young solar-type stars (0.5–1 Gyr) may drive winds up to about 30 times stronger than the present Sun. In the solar system, planetary auroral radio emission scales roughly with incident solar-wind power (the 'radiometric Bode's law', RBL; Zarka 2007), and Nichols & Milan (2016) have shown that RBL can be improved using the Dungey magnetospheric model. Enhanced winds should produce correspondingly stronger radio emission from planetary magnetospheres, meaning younger solar systems should be preferentially observable.

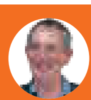
Facilities such as the Square Kilometre Array's Phase 1 low-frequency component (SKA1-Low) are designed to achieve microjansky sensitivities at 50–350 MHz (Braun *et al.* 2019). Model predictions suggest that present-day Earth analogues would be detectable only within a few parsecs, but stronger stellar winds or planetary magnetic fields could extend the detection horizon to roughly 8 ± 5 pc for Earth-mass planets and about 20 ± 10 pc for more strongly magnetised super-Earths (Grießmeier *et al.* 2007; Vidotto *et al.* 2015). Because the number of accessible systems increases with the volume of space surveyed, even modest increases in detection distance rapidly enlarge the observable sample.

> **"As instrumental sensitivity improves and the detection horizon expands, the available stellar sample increases steeply"**

By about 2030, early operations of SKA1-Low may enable the first direct detections – or strong constraints – on the magnetic fields of nearby giant exoplanets, primarily through direct planetary radio emission and potentially via initial Faraday-rotation experiments (Braun *et al.* 2019). After 2030, upgrades leading to SKA2 are expected to deliver roughly an order-of-magnitude improvement in radio sensitivity, along with much wider sky coverage and higher resolution, enabling far deeper studies of faint phenomena such as exoplanet magnetospheres.

The nearby (<30 pc) FGK stellar population spans ages from ≲ 0.1 Gyr to > 8 Gyr (Casagrande *et al.* 2011), providing a chronological sequence of solar-type wind evolution. As instrumental sensitivity improves and the detection horizon expands, the available stellar sample increases steeply. The number of local solar-type stars is already sufficient to support statistically meaningful studies once instrumental sensitivity reaches the required threshold. These studies open exciting possibilities, such as understanding solar wind-magnetosphere interactions during grand stellar activity minima and perhaps even during planetary main field reversals. ●

AUTHOR



Mike Lockwood was President of the RAS between May 2024 and May 2026 and is a professor of space environment physics at the University of Reading.

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The State-of-the-Art of Mercury's Space Environment in Preparation for the Nominal Phase of the BepiColombo Mission

Beatriz Sánchez-Cano and Alec McCrea report on the RAS Specialist Discussion Meeting that addressed recent results and future prospects in the study of Mercury

We stand at a unique moment, just before the first European mission arrives at Mercury. Exploring this planet is not just for science, it is a story of perseverance. The BepiColombo mission represents more than 25 years of hard work, meticulous planning, and international collaboration between Europe and Japan. From its conception to its launch in 2018, every step has been a technological and human challenge.

But the real adventure began after lift-off, after almost eight years of cruising through the inner solar system, a journey filled with complex manoeuvres and unexpected twists. Along the way, the spacecraft has performed multiple gravity-assist flybys of Earth, Venus, and Mercury itself, adjusting its trajectory with millimetre precision to overcome the Sun's immense pull. Each flyby has been an opportunity to collect unique data and test the mission's resilience under extreme conditions.

Now, on the threshold of its nominal science phase, BepiColombo is ready to unveil the secrets of a planet that challenges our theories about the formation and evolution of rocky worlds, a true odyssey that shows just how far human curiosity can take us.

On 12 December 2025, the Royal Astronomical Society specialist discussion meeting brought together scientists from around the globe, including the UK, Japan, the USA, Germany, France, Portugal, and many other European partners. The goal was twofold: to present the BepiColombo mission to the RAS audience and to foster fruitful discussions on collaborations with other missions, particularly solar observatories such as Solar Orbiter and Parker Solar Probe, which operate in Mercury's near environment and can provide complementary observations.

Meet Mercury

Mercury, the closest planet to the Sun, is profoundly shaped by its solar environment. Its magnetosphere reacts dramatically to solar transient events, coupling directly with the planet's surface. Even subtle shifts in the interplanetary magnetic field can instantly alter the magnetosphere's structure and redistribute plasma particles. During intense showers of solar energetic particles, this interaction becomes spectacular, sometimes causing Mercury's surface to glow and emit X-rays. These extreme responses make Mercury one of the most dynamic worlds in the solar system and a prime target for exploration.

Because Mercury's environment is so reactive to solar activity, it is essential for planetary and solar science communities to work together, and this was the main goal of this meeting. Coordinated efforts will allow us to refine our understanding of solar wind dynamics at 0.3 AU, improve forecasting of solar transients at such distances, and capture the holistic response of Mercury's magnetosphere, exosphere, and surface to these events, leveraging synergies with missions like Solar Orbiter and Parker Solar Probe.

(NASA / JHU Applied Physics Lab / Carnegie Inst. Washington)

"Mercury's environment is so reactive to solar activity, so it is essential for planetary and solar science communities to work together. This was the main goal of the meeting"

With that in mind, the two Project Scientists of BepiColombo, Geraint Jones (ESA) and Go Murakami (JAXA), took the audience on a journey through the mission's vision and challenges.

BepiColombo consists of two orbiters, the Mercury Planetary Orbiter (MPO) and the Mercury Magnetospheric

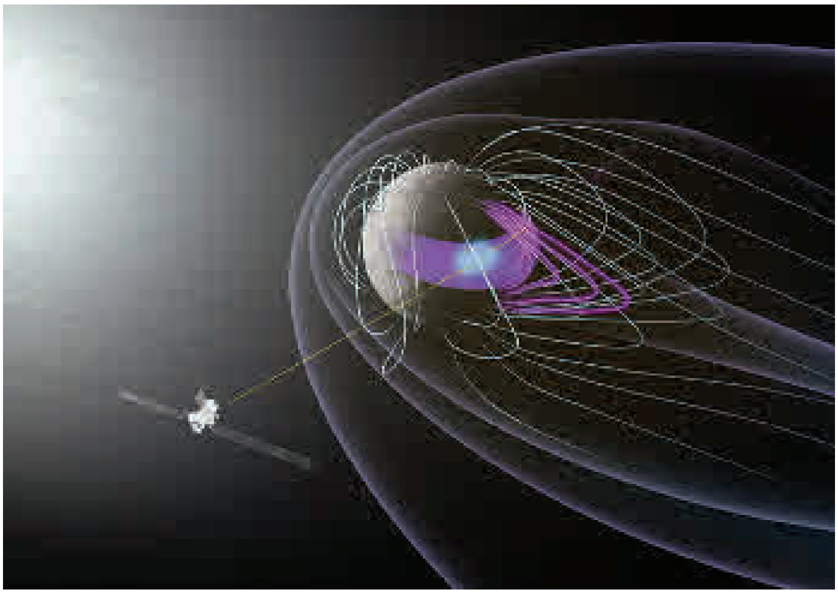
"An unprecedented opportunity to capture the entire chain of cause and effect from solar wind variations to Mercury's immediate response"

Orbiter (also called Mio), equipped to map Mercury's surface, probe its interior, and monitor its magnetosphere under intense solar conditions. Between both spacecraft, 16 instruments will operate in a coordinated manner to characterise the planet as never before, from two vantage points. The mission's goals span four themes: revealing Mercury's internal structure and massive iron core, decoding its volcanic and tectonic history, characterising its exosphere and magnetosphere, and performing precision tests of Einstein's General Relativity.

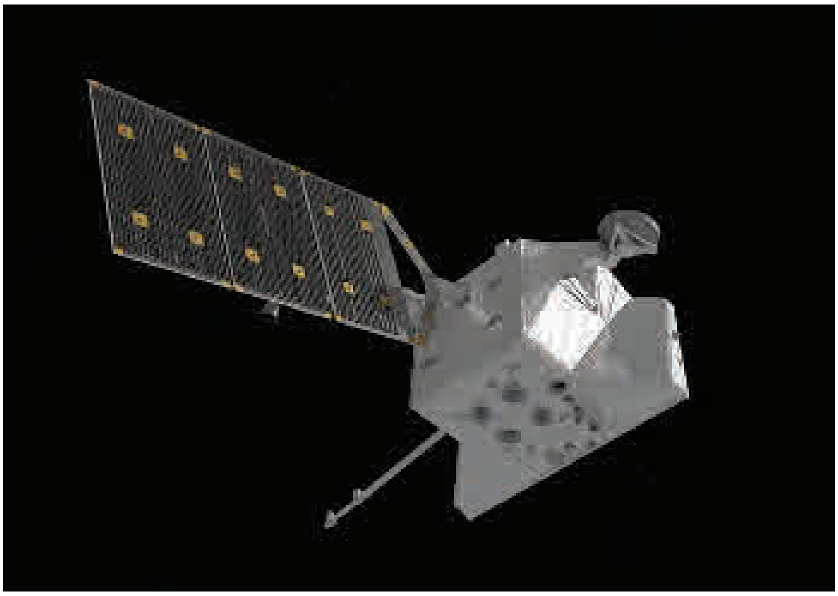
The RAS discussion meeting placed special emphasis on understanding Mercury's exosphere and magnetosphere, key elements of its dynamic space environment. One of BepiColombo's greatest strengths lies in its ability to deliver dual-point observations through its two orbiters. ESA's MPO will operate in a low-altitude polar orbit, focusing on detailed mapping of the surface and probing the planet's interior. Meanwhile, JAXA's Mio will follow a highly elliptical polar orbit, spinning as it measures magnetic fields and plasma in the surrounding space. This unique configuration enables scientists to study Mercury's interaction with the solar wind from two perspectives at once. For instance, when Mio is positioned upstream, outside the magnetosphere, it can precisely monitor incoming solar wind conditions. At the same time, MPO, deep inside the magnetosphere, records how those conditions reshape Mercury's magnetic field, drive plasma circulation, and even trigger particle precipitation on to the surface. These simultaneous measurements are essential for unravelling complex processes such as magnetic reconnection, plasma transport, and the coupling between the magnetosphere, exosphere, and surface. In short, BepiColombo offers an unprecedented opportunity to capture the entire chain of cause and effect from solar wind variations to Mercury's immediate response.

The long interplanetary cruise of BepiColombo has already taught us something remarkable: the solar wind near the Sun is far more variable and intense than expected. Changes in its speed, density, and magnetic structure are dramatic compared to what we observe near Earth. Understanding and characterising this variability is essential in order to maximise the scientific return of the mission once BepiColombo reaches Mercury. However, this region of the inner solar system remains one of the least explored, with very limited observations to date. That is why collaboration with other assets, such as Solar Orbiter and Parker Solar Probe, which operate in similar environments, is a major advantage. These partnerships will help us build a comprehensive picture of solar activity and its influence on Mercury, ensuring that BepiColombo's measurements are placed in the right context.

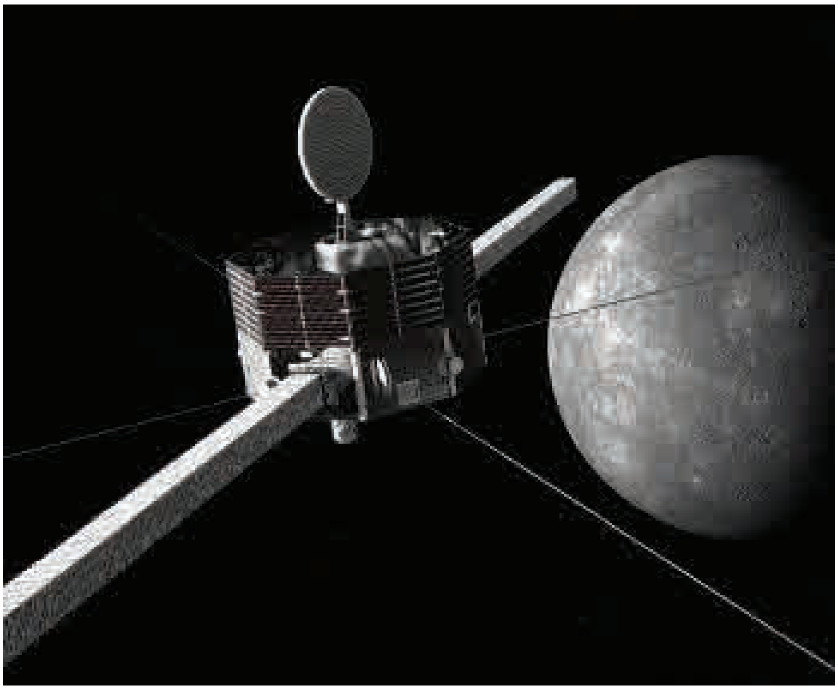
On this topic, the discussion featured representatives from Solar Orbiter and Parker Solar Probe, such as Georgios Nicolaou (University College London), alongside presentations showcasing BepiColombo's own observations during its cruise phase. These talks highlighted the mission's main discoveries



1 **BepiColombo transiting Mercury's magnetosphere during one of the cruise flybys, discovering new regions of the magnetosphere** (ESA, CC BY 4.0)



2 **Artist's impression of BepiColombo's Mercury Planetary Orbiter (MPO)** (ESA/ATG medialab)



3 **Artist's impression of BepiColombo's Mercury Magnetospheric Orbiter (also known as Mio)** (ISAS/JAXA)

related to solar transient events, such as coronal mass ejections (CMEs) and solar energetic particle (SEP) storms, at distances close to Mercury's orbit. These findings underline the importance of coordinated efforts between planetary and solar missions to fully understand the Sun's influence in this unexplored region of the inner solar system.

In particular, **Daniel Heyner** (Technische Universität Braunschweig, Germany), principal investigator of the MPO-MAG instrument, presented the latest insights into Mercury's dynamo and magnetospheric environment. His talk highlighted how simulations, modelling, and laboratory experiments are shedding light on the closure currents within the planet's interior, and how short-timescale magnetospheric dynamics can be explored in unprecedented detail by combining measurements from MPO-MAG with observations from the upstream Mio. Complementing this work, **Daragh Hollman** (Dublin Institute for Advanced Studies) introduced a new framework for studying Mercury's magnetic field. They revealed a statistical, predictive approach for identifying magnetospheric boundary crossings, based on a random-forest classifier trained using data from NASA's MESSENGER mission. This method promises to enhance significantly the interpretation of magnetic field measurements from both Mio and MPO.

The Leicester-led MIXS team outlined the scientific objectives, key areas of interest, and cruise-phase discoveries of the X-ray spectrometers aboard MPO. MIXS principal investigator **Emma Bunce** (University of Leicester) described the instrument's goals, which include producing accurate, spatially resolved global abundance maps and investigating electron-induced X-ray fluorescence from Mercury's surface. Although MIXS spent much of the cruise phase enclosed within the spacecraft stack, **Simon Lindsay** (University of Leicester) demonstrated its unexpected capabilities as a cosmic-ray detector. During brief operational windows, the team found that interaction rates tracked the solar cycle rather than heliocentric distance, offering valuable insights into the radiation environment.

Researchers from the University of Michigan revisited findings from NASA's MESSENGER mission to Mercury and highlighted how they inform future exploration. **Ryan Dewey** (University of Michigan, Ann Arbor) presented evidence of systematic seasonal variations in the solar wind driven by Mercury's highly elliptical orbit, and showed how these variations strongly affect the planet's magnetosphere through compression and magnetic reconnection. **Jim Raines** (University of Michigan, Ann Arbor) focused on the impact of intense coronal mass ejections, explaining how helium ions carried by CME-driven solar wind enrich Mercury's regolith. This process leads to a delayed enhancement of sputtered helium ions in the exosphere. Both speakers emphasised how a two-spacecraft mission configuration will open new avenues for investigating these coupled solar-wind–magnetosphere–surface interactions. Another important aspect to consider in this type of extreme interaction if the sodium exosphere also produced by solar wind interactions with the surface. To address this topic, **David Rees** (University College London) presented the Mercury Sodium Atmosphere Spectral Imager (MSASI) instrument aboard JAXA's Mio spacecraft. MSASI is designed to investigate key processes governing Mercury's surface-bounded exosphere by measuring the distribution and temporal evolution of sodium released from the regolith. These observations will help clarify how regolith–exosphere–magnetosphere interactions operate, revealing the mechanisms by which sodium is generated, transported, and ultimately lost to interplanetary space.

With both Mio and MPO carrying active radiation monitors throughout much of the cruise phase, teams also reported on observations of solar energetic particles in the inner heliosphere. **Gaku Kinoshita** (University of Tokyo) described how measurements from Mio's radiation monitor have been coordinated with STEREO-A and SOHO to study solar energetic particle propagation, with additional opportunities arising from joint observations of interplanetary coronal mass ejections alongside Solar Orbiter and Earth-based spacecraft, as well as the detection of cosmic rays during Mercury fly-bys. **Marco Pinto** (Laboratory of Instrumentation and Experimental Particle Physics, Lisbon) outlined future plans to use data from both detectors to study Mercury's magnetospheric response to solar energetic particles and develop models of particle propagation, and investigate surface composition using complementary measurements from both spacecraft.

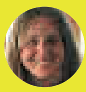
"Particular attention was devoted to Mercury's response to solar activity, highlighted by the strikingly different views of the planet captured during the six BepiColombo flybys"

Particular attention was also devoted to Mercury's response to solar activity, highlighted by the strikingly different views of the planet captured during the six Mercury flybys performed by BepiColombo throughout its cruise phase. Each encounter revealed an unexpectedly diverse picture of Mercury's environment, particularly on its electron environment. These findings were discussed by **Mathias Rojo** (IRAP, Toulouse). It was followed by **Léa Griton** (Sorbonne Université, Paris) who presented new developments in global simulations of Mercury's magnetosphere aimed at understanding the behaviour of the most energetic particles. By combining electric and magnetic fields derived from magneto-hydrodynamic (MHD) simulations with guiding-centre particle codes, their work explores how particle lifetimes vary under different solar wind conditions, offering deeper insight into the highly dynamic and solar-driven nature of Mercury's space environment.

Following the meeting, **Go Murakami** (JAXA), project scientist for Mio, and **Lina Z. Hadid** (LPP, Paris), principal investigator of the MSA instrument, provided an overview of the mission and highlighted the key scientific themes to be explored at the upcoming A&G Highlights Meeting. Their presentation served as an excellent summary and a fitting close to an inspiring and information-rich day.

The meeting was highly active and productive, and we expect it to mark the beginning of new collaborations and discussions, particularly as BepiColombo enters orbit and the nominal mission unfolds, an exciting prospect that we hope will bring the community back together at future RAS meetings. ●

AUTHORS



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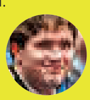
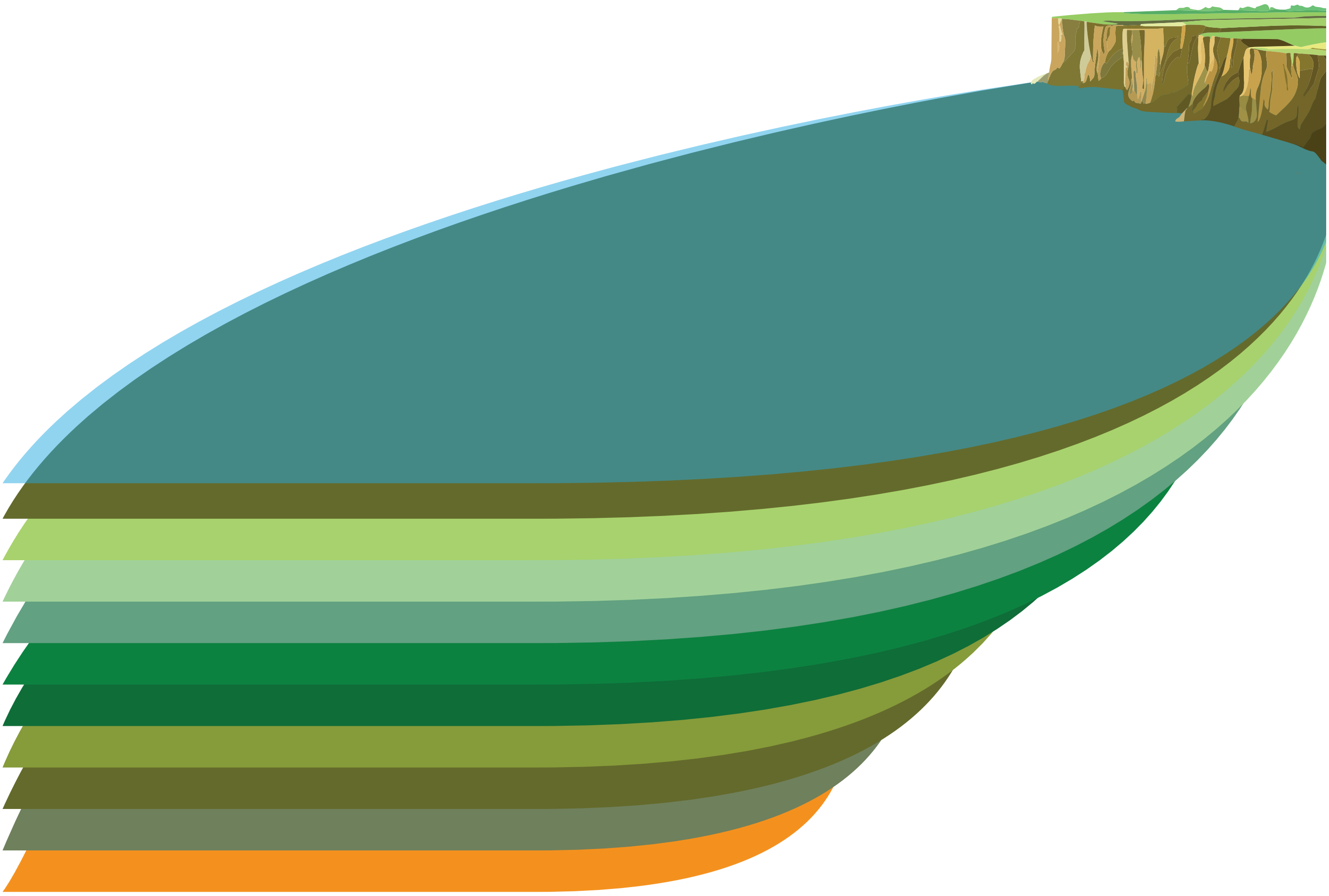


Alec McCrea (ajm149@leicester.ac.uk) is a PhD student at the University of Leicester studying magnetosphere-surface interactions at Mercury.

The UK and Ireland Geophysical Array



In the first of two companion papers, Andrew Curtis, Karen Lythgoe, Stephen Hicks, Lidong Bie, Dominik Strutz, Emma Chambers and UKI-Array contributors set out the overall concept of a potentially game-changing new geophysical antenna

Scientific exploration of the UK and Ireland's subsurface has brought important contributions to scholarship and prosperity for both people and the planet. But an array of seismological instruments spanning the UK and Ireland (UKI-Array), augmented by other types of geophysical sensors, could maximise the value offered by existing equipment pools. Researching natural phenomena and structure in the deep and shallow Earth may solve problems concerning hazards and resources, connect scientists to schools and the broader public, and thus inspire a new generation to learn about geophysics.

The UK and Ireland are currently situated within a tectonically stable continental region, with neither active volcanoes nor major fault ruptures. Yet their shared subsurface has consistently proven to be both fascinating and critically important. Subsurface hazards such as moderately sized earthquakes pose a substantial risk to critical engineering sites (e.g. Tromans *et al.* 2019, Mosca *et al.* 2022, Lebedev *et al.* 2023). In turn, subsurface engineering projects may trigger earthquakes (Verdon *et al.* 2025) or risk contaminating water resources (Stuart 2011, Smedley *et al.* 2024). Subsurface material properties can vary under the influence of stress, temperature or precipitation changes, leading to landslides or mass movements (Pennington *et al.* 2015). The subsurface is also a crucial source of natural resources such as water, rock, soil, heat, minerals and hydrocarbons (Allen *et al.* 1997, Deady *et al.* 2023, Murtaza *et al.* 2021, Patton *et al.* 2025, Scanlon *et al.* 2023). It is a natural option for compressed-air, gas or hydrogen-based energy storage (Evans *et al.* 2018, Williams *et al.* 2022), storage of excess heat for later release (Reuss 2015, Fraser-Harris *et al.* 2022),

"Imaging the Earth's subsurface provides critical clues to its geological history and the tectonic processes that shaped it"

and for waste products such as spent nuclear fuel (Tweed *et al.* 2015, Pavey *et al.* 2025) and the vast quantities of CO_2 that must be locked away from the atmosphere to mitigate future climate change (Haszeldine 2012). Imaging the Earth's subsurface also provides critical clues to its geological history and the tectonic processes that shaped it (Bonadio *et al.* 2021, Galetti *et al.* 2017, Nicolson *et al.* 2014).

Each of these perspectives on the subsurface carries social, engineering or economic risks related to the geology and variability of Earth dynamics, yet each risk of natural or engineered hazards comes with opportunities for mitigation based on scientific knowledge and observational data. Obtaining information about the subsurface can involve operations such as drilling or excavation, which are expensive and invasive and only cover a limited volume. It is therefore important to be able to explore, image and monitor changes in the subsurface, at a wide range of scales, remotely.

Key sources of data

The primary source of remotely sensed information is geophysical. Geophysicists use measurements of the seismic, electrical, electromagnetic and gravitational energy (amongst others) to infer properties of the Earth's surface or interior. In particular, seismic waves from active sources, from earthquakes, and from more distributed energy sources (referred to as ambient seismic noise), contain information about both the sources themselves and the structure and properties of the Earth. As a set of islands, the UK is bombarded from all directions by ambient noise created by oceanic waves. By analysing recordings of these waves and other signals recorded on dense arrays of sensors, geophysicists can construct 3D images of crucial properties of the subsurface. Monitoring changes over time reveals processes active inside the Earth across multiple scales of time and space.

Thanks to the seismic stations operated by the British Geological Survey (BGS) and AWE Blacknest in the UK, and the Irish National Seismic Network (INSN) in Ireland (BGS 1970, Blacknest 1960, DIAS 1993), and to the recent temporary broadband station deployments in Ireland, the lithosphere and underlying mantle beneath large parts of the United Kingdom, Ireland, and surroundings can now be imaged (e.g. Bonadio *et al.* 2021). These data can help us to de-risk geothermal energy exploration (Chambers *et al.* 2025), better assess subsurface mineral resources (e.g. Roy *et al.* 2026), and determine what controls the distributions of seismicity and seismic hazard (Mosca *et al.* 2022). However, substantial gaps in the station coverage across Britain and Ireland remain and attempts to image the crust and mantle beneath the region have been unable to resolve details less than several tens of kilometres across (Nicolson *et al.* 2014, Luckett & Baptie 2015, Bonadio *et al.* 2021, Zhao *et al.* 2026). This poor resolution is due to the limited number of sensors in the permanent seismic network; this sparsity similarly limits our ability to detect and locate small natural earthquakes and other seismic sources, for example to attribute them to specific fault zones and use them to alert us to the possibility of larger future events (Roy *et al.* 2021, Watkins *et al.* 2023), or to distinguish between natural and anthropogenic causes (e.g. Hicks *et al.* 2019).

Currently, the UK has a large number of seismic sensors (see Table 1), many of which were acquired recently to form the LeNS-UK community facility, funded by the

Institution	Equipment
Dublin Institute for Advanced Studies	• 65 3C SmartSolo • 134 1C SmartSolo • 20 BB • 2 DAS interrogators
University of Oxford	• 21 Raspberry Shakes • 280 STRYDE nodes • 6 BB • 13 Güralp Certimus BB seismometers + solar panels • 420 Sercel WiNG DFUs (1C BB MEMS) • 10 mounting plates for 3C configuration (Galperin) • 1 DAS interrogator (Sintela)
University of Aberdeen	• 6 Güralp Certimus • 10 Güralp 6TD • 102 3C SmartSolo nodes • 20 Raspberry Shakes
Birkbeck	• 3 Raspberry Shakes
University of East Anglia	• 1 Güralp 40T • 2 Raspberry Shakes • 1 DAS interrogator
Strathclyde University	• 7 3C SmartSolo
University of Leeds	• ~50 3C SmartSolo • 1 DAS interrogator (Febus)
University of Edinburgh	• 21 3C SmartSolo
University College London	• 5 Güralp BB quick deploy kits
British Geological Survey	• ~20 BB • EIDA system to store data
University of Cambridge	• 5 x 120s Trilliums
University of Bristol	• 4 Güralp Certimus • 6 Trilliums • 1 DAS interrogator
Cardiff University	• 3 Güralp Radian
British Antarctic Survey	• 32 3C SmartSolo • 2 Güralp Radians
Seis-UK (University of Leicester)	• Many BB + dataloggers + solar panels
LenS-UK (University of Cambridge)	• 200 3C SmartSolo • 1980 1C Stryde nodes (~50 days recording time)
Imperial College London	• 1 Güralp ESP
SEIS-UK Equipment Pool	• 189 BB (various makes/models) • 37 High Frequency Seismometers (36 Polar Pegasus; 1 Geode) • 20 Pegasus & Trillium Compact (NERC Urgency Pool)

Table 1 Seismological instrumentation held at institutions around the UK and Ireland (BB: broadband).

"Substantial gaps in the station coverage across Britain and Ireland remain, and attempts to image the crust and mantle have been unable to resolve details less than several tens of kilometres across"

Natural Environment Research Council (NERC). While subsets of similar sensors have been used successfully for smaller, bespoke projects related to the goals of individual research groups (e.g. Hudson *et al.* 2024), it is also timely to consider whether an integrated ambition to combine these sensors with other existing pools of equipment in the UK and Ireland to tackle combined objectives could lead to scientific and technical advances that would benefit the UK Earth science and other related communities.

Complementary to seismic imaging, magnetotellurics (MT) is a deep-sounding passive electromagnetic method that images electrical properties (influenced by, e.g. the presence of fluids, melt, metallic minerals) to great depth (1–1000km). Backbone, long-period MT data can be used to investigate lithospheric structure, space weather impacts, and characteristics of specific targets such as fault zones, as well as for geothermal and mineral exploration (e.g. lithium in geothermal brines hosted in fractured rocks and sulphide deposits – see Hübert *et al.* 2025). Other electromagnetic and electrical methods allow the top kilometre or so of the Earth's subsurface to be interrogated in greater detail.

Adding acoustic sensors to seismometer locations allows airborne infrasound waves to be recorded. Infrasound recorded across a network of such sensors can assist in improving our understanding of dynamic atmospheric process including middle-atmosphere wind variability. When combined with seismic recordings, infrasound data can also provide valuable information about the partitioning of energy between the subsurface and atmosphere for near-surface events (Greene *et al.* 2009).

The UKI-Array concept

The concept of such a combined collection of sensors is referred to here as the UK and Ireland Array (UKI-Array). In order to test and develop a community vision for the UKI-Array, a small team (the first six authors) created an initial draft of a green paper (a conceptual proposal). Through the British Geophysical Association's email list (geophysics.org.uk/sign-up/), they invited the UK geophysical community to comment and add potential opportunities, applications and implications of such an array. The team consolidated these contributions, then organised a hybrid Specialist Discussion Meeting in London and online, hosted by the Royal Astronomical Society on 10 October 2025. They issued an open invitation to the geophysical community to use the meeting to discuss the vision, the design of the array, how the data might inform the wide range of interests of the community, and to voice concerns about deployment, funding and a range of other aspects. There was a strongly positive response to the UKI-Array concept, a wide range of proposed applications and outreach opportunities from the array deployment itself, and a clear signal from the community to move this concept forward based on proposals in the green paper and subsequent discussion. These proposals and discussions are summarised here to form a consolidated description of the UKI-Array initiative and its potential applications.

In this article, we describe the UKI-Array concept in more detail. Then we list a snapshot of the equipment available across the UK and Ireland, and discuss

1 Top left: **SmartSolo node battery packs under charge; Bottom left: A broadband seismometer being deployed, ready to be covered then buried; Bottom right: A subset of the 1980 Stryde nodes at the LeNS-UK facility; Top right: Phoenix MTU-5C ultra-wideband magnetotelluric receiver close to Coire an t-Sneachda.** (Nick Rawlinson, Juliane Hübert, Jack Andrew Smith, University of Edinburgh) conceptual end-member designs. In the companion paper Curtis *et al.* (2026) in the next issue of *A&G*, we describe the various ideas and opportunities for UKI-Array, namely: to explore surface processes and environmental geophysics; to image the subsurface of the UK and Ireland landmass and surrounding seas; to monitor and model earthquakes, hazard and risk; to investigate potential Earth resources and subsurface storage; and finally to illuminate structure and properties of the deeper Earth.

The UKI-Array concept comprises thousands of seismic sensors deployed across the UK and Ireland. This baseline seismological array may be augmented by seismometers on the seabed and in neighbouring countries across the English Channel and North Sea, and by a range of other complementary geophysical sensor types. The resulting data will provide detailed models of the Earth's crust under the UK and Ireland, high-resolution images of key fault zones, and, over the deployment period, information about both natural and anthropogenic seismic activity, including low-magnitude earthquakes commonly associated with industrial or other anthropogenic activity. The array will be designed to answer fundamental scientific questions about the shallow and deep Earth, and to address important issues relating to the future use of the Earth's subsurface both as a source for sustainable energy and resources, and as a means of storage for energy and waste. In addition to subsurface applications, parts of the network could be used for near-surface environmental applications, such as the close-range sensing of properties that control geomorphic processes – landslides, floods, water table changes, and sediment transport (Bainbridge *et al.* 2022). The data would be openly available, and a significant component of the activity would focus on public engagement.

The existing network of permanent seismic sensors reliably detects events of magnitude greater than M ~3.0 anywhere in the UK; in Ireland this so-called magnitude of completeness is M ~1.2 (Baptie 2018, Mosca *et al.* 2022, Möllhoff and Bean 2016, Möllhoff *et al.* 2019, Musson & Sergeant 2007). Yet tens of thousands of smaller magnitude earthquakes remain undetected each year. There is a pressing need to enhance our ability to detect small earthquakes to facilitate the monitoring, derisking, and regulation of industrial activities in the upcoming era of subsurface waste and energy storage, and sustainable resource production (Karamzadeh *et al.* 2021). The short-term deployments in the UKI-Array would therefore be designed in part to provide significantly updated images and information about the UK's subsurface structure and faults, as well as offering an initial test of the monitoring capability of a dense, optimally-designed array of heterogeneous sensor types.

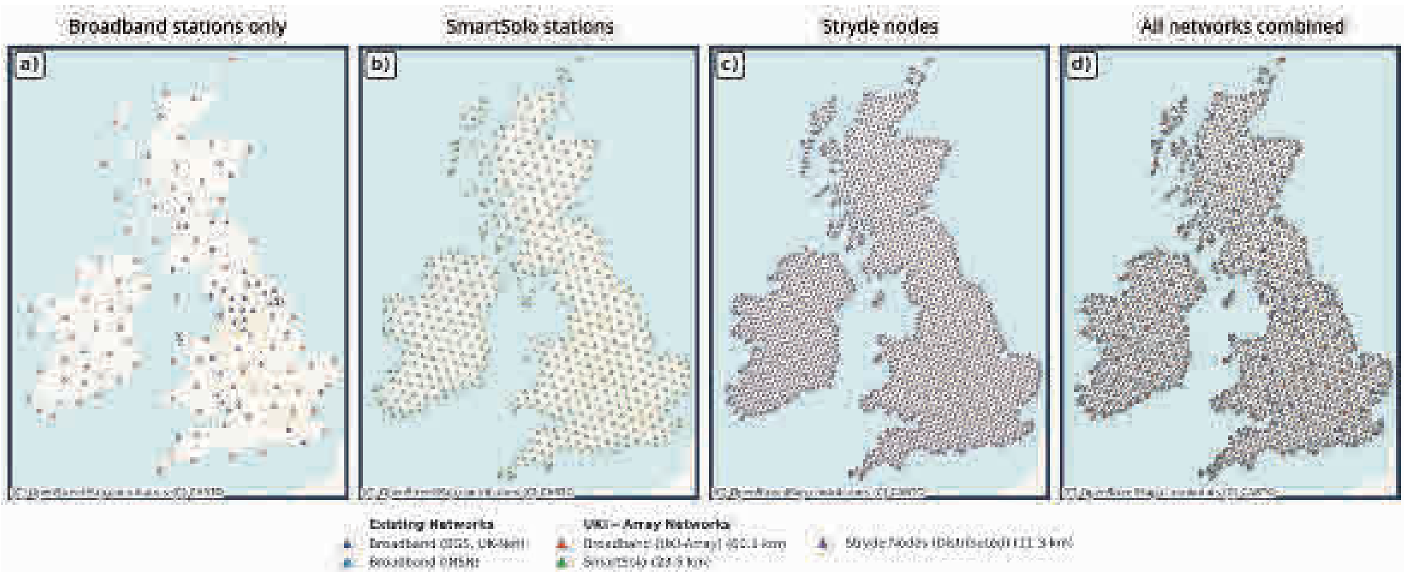
Geophysical equipment

Table 1 lists the seismological sensors currently held in institutions around the UK and Ireland. Ocean bottom seismometers are also available, including ~60 at the Ocean Bottom Instrumentation Consortium (OBIC) arm of the NERC-funded Geophysical Equipment Facility (GEF). These are not listed in Table 1 because deployment of seabed sensors is relatively expensive, so they are not included in the array designs presented below. If the opportunity to include them materialises then designs will be updated. A number of Raspberry Shake seismometers have also not been included because these are typically deployed in people's houses, so their locations are not shared publicly. Nevertheless, with appropriate data quality checks they can enhance earthquake catalogues by detecting small events that would otherwise go unnoticed by national networks alone, and their low cost makes them valuable tools for public outreach.

A significant portion of the available equipment is provided by LeNS-UK – a NERC-funded instrumental facility that was established in September 2025. LeNS-UK hosts two types of seismic nodes, shown in figure 1. There are 1980 Stryde Range+ nodes, which are small, compact instruments containing a single component accelerometer that can record for 50 days, and 200 SmartSolo nodes, which contain 3-component geophones with a longer period response, that can record for over 30 days.

In the UK and Ireland seismological community, there are also many smaller pools of broadband seismometers, which record to a much lower frequency response, and can detect long-period teleseismic surface waves and enable full-waveform source and structure imaging, for example. Broadband seismometers, solar panels, and support can also be provided by NERC's SEIS-UK facility, which is part of the GEF. SEIS-UK hosts a large number of broadband instruments for community use, which will strongly complement the denser short-period node networks.

"The network could be used for environmental applications, such as the close-range sensing of landslides, floods, water table changes, and sediment transport"



2 Illustration of sensor density and spacing achieved if existing broadband stations combined with SmartSolo and Stryde seismic nodes are distributed evenly across the UK and Ireland. The average inter-station distances are shown in brackets in the legend. SEIS-UK equipment has not been included.

The large volumes of seismological data (likely to total tens of terabytes) collected would be stored on the British Geological Survey's EIDA storage and retrieval node. EIDA is the European Integrated Data Archive network, which shares seismic data between data provision and compute servers internationally. This will ensure that the data are widely available in standard formats, according to the FAIR Data Principles (Findable, Accessible, Interoperable, Reusable), and can be run through standard as well as bespoke processing sequences.

Recently, the NERC GEF acquired 10 new broadband magnetotelluric (MT) systems, providing the community with this much-needed infrastructure, while the British Geological Survey (BGS) operates several additional instruments. Similarly, the Dublin Institute for Advanced Studies (DIAS) MASTER Infrastructure hosts 12 ultra-wide band MT systems and 20 long-period MT systems. Additional types of geophysical instrumentation that probe the electrical properties of the subsurface are of potential interest at smaller spatial scales. Several universities and companies in the UK own Electrical Resistivity Tomography (ERT) equipment, used to image the electrical conductivity structure of the upper tens of metres of the crust. Active-source electromagnetics has also been suggested: one such system that uses a current bipole source and electric field receivers can penetrate to depths of around two kilometres, and the NERC GEF has a transient electromagnetic instrument (TEM), both systems hosted at the University of Edinburgh.

Fibre-optic based, distributed acoustic sensing (DAS) systems measure dynamic strain, such as that caused by seismic waves, along the one-dimensional profiles of optical fibres laid on the surface or buried. The key advantage of these systems is that they can be used to record seismic energy at spatial intervals of the order of one to tens of metres along a cable length of up to approximately 100km. Although burying cables can be time-consuming and logistically challenging and DAS data volumes tend to be huge, several systems are available in the UK and Ireland (including one at the University of East Anglia that is a NERC-funded community asset) which may be used to complement either dense local arrays or large-scale linear arrays, and it is also possible to connect DAS interrogators to existing subsurface fibre that was originally deployed for other purposes such as telecommunications.

Design components and potential targets

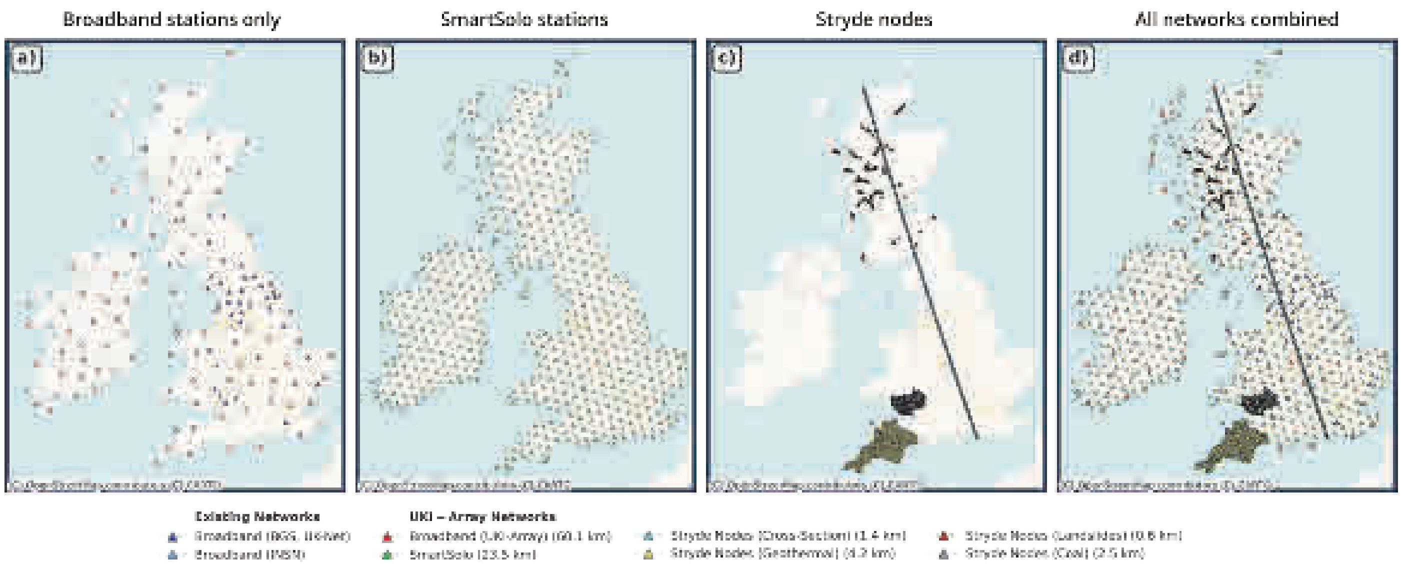
The UKI-Array array concept consists of one or more of the following six components:

1. A distributed network of more than 2000 seismic sensors across the UK and Ireland
(a concept design is shown on the right of figure 2), with further sensors possibly deployed offshore.

This network would remain in place for at least two months. Several studies suggest that one month (the battery life of SmartSolo nodes) is long enough to obtain both stable cross-correlations for imaging with ambient noise and to estimate coherencies in spatial and temporal local wavefield gradients (Nicolson *et al.* 2014, Cao *et al.* 2020). This would need to be checked for the higher frequency Stryde nodes, and the feasibility of longer deployment times for nodes can be considered. This component would deliver a snapshot of seismicity across the UK and Ireland over the survey period, providing the first uniformly dense catalogue of earthquake locations (figure 2d). It would produce new high-resolution, homogeneous images of the crust and upper mantle from surface and body waves. Shallow crustal models would have commercial value, while improved knowledge of faults and stresses would help to identify areas at higher risk of induced seismicity from future subsurface activities. The dataset would support studies of deeper Earth processes of broad national and international interest, and constrain crustal seismic attenuation, improving magnitude estimates for small, induced earthquakes and thus aid regulation of industrial activity.

2. Clustered, potentially transportable arrays involving subsets of sensors deployed more densely around specific targets of interest, such as to test scientific hypotheses, or to image or monitor potentially active faults, landslide/flood risk hotspots, and geological targets with economic value.

The concept is illustrated in figure 3c, focusing on granites of geothermal interest in the south-west UK, potential coal mine hazards such as in South Wales that also create opportunities for subsurface heat storage and extraction, and areas of potential landslides or mass movements in Scotland and northern England. This component also includes small linear arrays to characterise major fault lines that segment the UK and Ireland along north-easterly trending boundaries. It would generate



3 **Illustration of an array in which the current broadband equipment and SmartSolo nodes in Figure 2 are still distributed according to design component 1 (evenly spread), while all Stryde nodes are used for design component 2 (focused sub-arrays around targets of interest). The average inter-station distances are shown in brackets in the legend.**

high-resolution images of selected shallow and deep crustal and upper-mantle targets across the UK and Ireland using surface and body waves. It would allow for detection and characterisation of hazardous surface processes in noisy environments. A focused sub-array in south east England, for example, would address the London monitoring gap and establish baseline data for subsurface resource exploration and future production, and for subsurface storage.

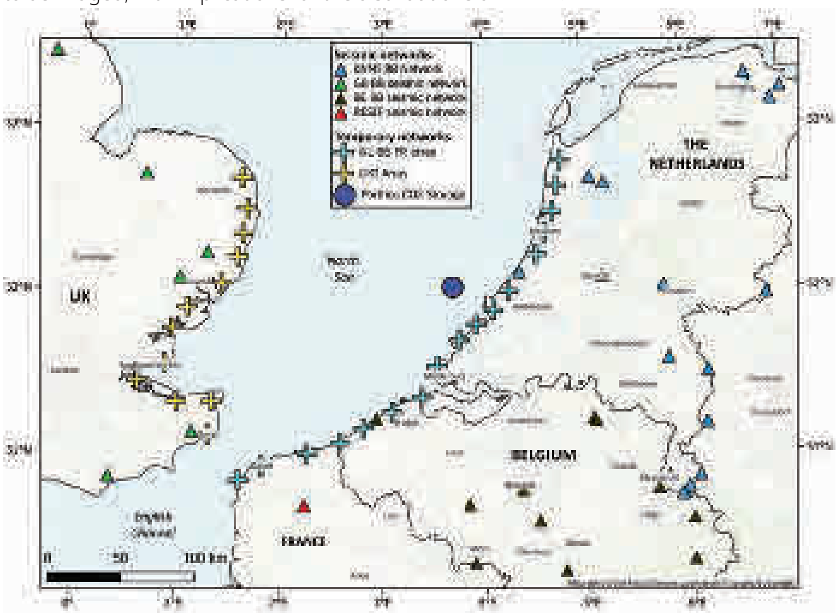
"Engagement with the public and schools will also help with site hosting, data use and education, requiring substantial organisation"

3. A linear array stretching approximately north-south across the length of the UK, that crosses major ancient tectonic suture zones (figure 3c).

This array would broadly follow a 1974 active-source seismic survey (Bamford *et al.* 1976) with the aim of clarifying relationships between major geological boundaries. The UK and Ireland are dominated by NE–SW and E–W orogenic belts formed during successive mountain-building events, but key aspects of their tectonic evolution, such as past subduction zone locations, remain under debate. An extremely dense linear array would provide an unbiased transect of information interrogating the properties of known geological boundaries, faults with less obvious surface expression, and the heterogeneous material characteristics of intervening regions.

4. An additional network of temporary broadband seismic stations (or re-deployment of existing stations in new locations) deployed for two or more years to ensure successful application of a range of passive seismic imaging techniques (illustrated in figure 2a and 2b for a conservative addition of only 20 broadband sensors). The new locations will fill gaps in the broadband-station coverage provided by the current configurations of the permanent seismic networks in the UK and Ireland.

This broadband network would allow the seismic and thermal structure of the crust and underlying mantle to be imaged, with implications for the distributions of seismicity, seismic hazard, geothermal energy and mineral resources. Broadband seismometers play a major role in larger magnitude earthquake characterisation, and this capability would improve across most of the region.



4 **Conceptual design of an international component of the UKI-Array concept. In collaboration with Dutch, Belgian and French seismologists, the array including low-frequency nodes and seismometers could improve North Sea monitoring to image structures of scientific and economic interest beneath the offshore seabed surrounding the UK and Ireland, such as around the Porthos CO_2 storage site (circled) or around new windfarms or energy islands in the North Sea.**

5. Other types of sensors may be added to any of these campaigns, for example, to probe gravitational, electrical, magnetic, electromagnetic, or acoustic effects and properties of the Earth's (sub)surface and atmospheric processes.

This component extends the seismological backbone array components to the wider geophysical community, enabling shared deployment logistics (e.g. co-location may allow power supplies and land access rights to be shared). It would support MT studies at scales similar to Component 1, complements Component 2 with electrical resistivity and active-source electromagnetics, and may include acoustic sensors and fibre-optic distributed acoustic sensing alongside selected seismic arrays.

6. Coordinated synchronous arrays on opposite coasts of the English Channel, North Sea and Irish Sea would allow offshore subsurface structures to be imaged (figure 4) and offshore seismicity to be better characterised. Ocean bottom seismometers from OBIC (UK) and DIAS iMARL (Ireland) pools could be used to significantly improve off-shore seismicity monitoring and subsurface imaging.

Component 6 extends the array offshore to support seismic monitoring of CO_2 sequestration in the Southern North Sea (e.g. TNO 2025), which has a fairly high seismicity rate compared to on-land Britain. Accurate event locations require high-resolution velocity models (Verdon *et al.* 2013, Strutz & Curtis 2025), but S-wave structure remains poorly constrained (Jerkins *et al.* 2025). Coordinated coastal deployments across northwest Europe and the UK would enable ambient noise tomography to refine deep velocity models and strengthen offshore monitoring.

Discussion and next steps

In this the first of two companion papers we have set out the overall concept of the UKI-Array, and various design components. A variety of other considerations must be integrated to create a final, specific design. Our conceptual designs were primarily developed to estimate average inter-station distances given the equipment that is readily available. Ultimately these designs must be optimised jointly to maximise both coverage and resolution of tomographic imaging, and earthquake monitoring efficacy, given potential land access constraints (Curtis *et al.* 2004, Mordret & Grushin 2025, Strutz *et al.* 2025).

It would be useful to test the performance of Stryde nodes at long inter-node distances and low frequencies, both as single-component (vertical) sensors, or when operating as three-component seismometers to record shear waves (using three orthogonally oriented nodes per location). For ambient noise seismic interferometry and imaging, the same noise field must be recorded by pairs of sensors at different locations. Ambient noise tomography is therefore affected by the degree of seismic wave attenuation, and by the spatial coherency of ambient seismic noise across the UK and Ireland. While a previous test has already shown that ambient noise imaging works well with Stryde nodes in either one- or three-component mode, with up to at least 6km inter-node spacing in Cornwall, this was only possible because the manufacturer removed the nodes' standard low-frequency cut-off. Local test deployments in other regions would therefore be a good way to quantify uncertainties before designing the final array.

The array(s) will require large-scale deployment, servicing, and recharging across much of the UK and Ireland, with different sensor types operating at national and sub-array scales. Beyond the clear educational benefits, engagement with the public and schools will also help with site hosting, data use and education, requiring substantial organisation. Fair fieldwork contributions from all partners across different regions of the UK and Ireland, and joint effort to obtain site permits, are also important. One idea would be to promote the project prior to deployment so that members of the public can register their interest in hosting a sensor, helping to ensure secure deployment.

A challenge that may constrain deployment of the various components of the array is that relatively few sources of science council funding allow fair distribution of resources between the UK and Ireland. This is a significant barrier to deploying multi-national arrays more generally, and may require that the UK and Irish parts of the UKI-Array are deployed during offset time periods, or with different levels and types of resourcing. This will require that the survey and logistical design methods are flexible and responsive to changing opportunities, as they arise.

In this paper we have discussed the concept and design of the UKI-Array, and some of its benefits. In a companion paper in the subsequent issue of *A&G* (Curtis *et al.* 2026) we explore in more detail the specific applications and opportunities enabled by the dataset. This reveals the value offered by such an initiative, contributing to a justification of the effort and expense required. Together these papers form a coherent argument for the community to progress this initiative to a funding proposal, and to eventual implementation. ●

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Welcome to your universe!

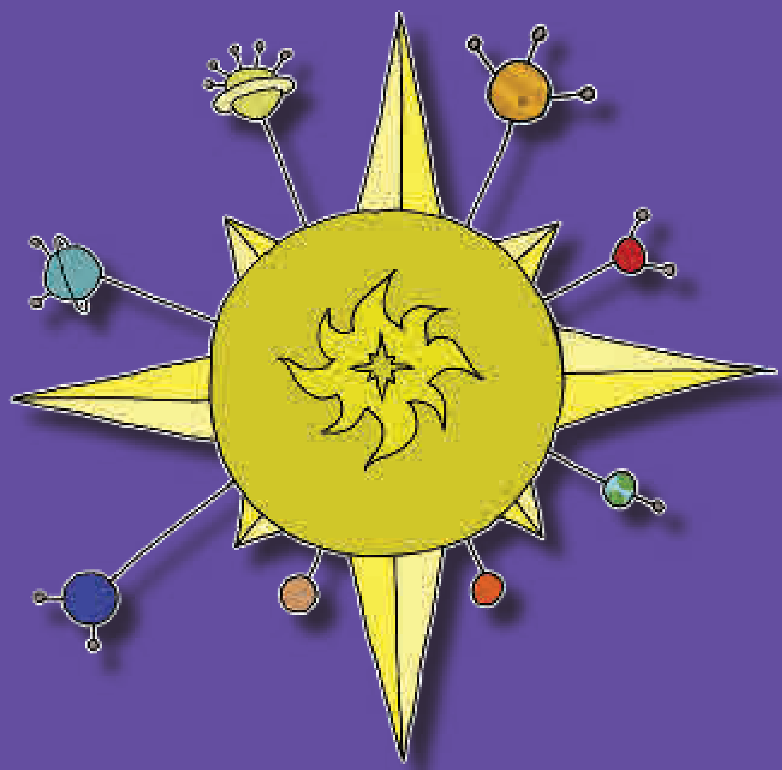
The National Astronomy Meeting (NAM) came to Durham University with a deceptively simple idea: put community front and centre. Lorraine Coghill, on behalf of the engagement team at Durham, sets out how they reimagined the academic conference.

What happens when community is woven into the very heart of a national scientific meeting? By embedding exhibitions, co-created art, public events, and school and community projects directly into the heart of the National Astronomy Meeting, NAM2025 demonstrated how integrating public engagement into the daily life of a scientific conference can bring a positive energy, elevate confidence in young people, challenge assumptions within the research community, and create conversations rarely possible in standalone outreach. Here, the conference organisers recount their experiences; outlining the initial findings of our evaluation; and highlight the lessons we hope will inform, inspire and strengthen future conferences and events.

Designed around connection

In July 2025, the National Astronomy Meeting (NAM) came to Durham University with a deceptively simple idea: put community front and centre. From the outset, we were committed to community sitting at the heart of NAM2025 and so 'Community: Science through connection' was chosen as our theme, reflecting our belief that astronomy thrives when diverse groups (researchers, young people, artists, industry partners and the wider public) are brought together meaningfully and authentically. At a time when many across the UK and beyond, including in our academic communities, feel disconnected or under pressure, we wanted NAM2025 to demonstrate and celebrate what collaboration can achieve, and to create an inclusive, welcoming atmosphere that purposely involved people who might not otherwise encounter astronomy or attend an academic conference. For us, welcoming NAM2025 was a privilege and opportunity, and we were determined that the benefits of bringing so many astronomers to Durham would be shared widely with communities in the North East.

This determination played out in looking at NAM2025 not as a one-off, one-week event, but as an opportunity to bring together long-term engagement programmes and involve regional and national partners. Projects had to be collaborative, meaningful, and authentically involve and represent the community participants. For this to work, NAM2025's public engagement had to be embedded into the conference programme and not just an add-on, or be after hours or in a different location. Engagement had to be within the space where astronomers experienced the conference. The theme wasn't just a slogan for us, it was a principle that shaped choices about partners, place and priorities.



Artwork from Celestial Fingerprints (© Lizzie Lovejoy)

"We wanted to show what collaboration can achieve, to embed public engagement into the conference programme, not just as an add-on"

That principle did more than diversify the programme. It changed who the conference was for. Delegates shared space with local youth groups, teachers, creatives, and families. Artists felt at home in a science venue. Members of the public participated in sessions. Crucially, by drawing on long-term relationships, community partners arrived with trust, knowing their involvement was valued.

Feeling the buzz

Even before delegates stepped into Durham's Teaching and Learning Centre (TLC), it was clear that NAM2025 was no ordinary scientific conference. Outside, people queued to board the stunning Moon Palace (artwork, observatory, and space for conversation, star-gazing, creative exploration and cosmic tea). Inside the TLC, the walls carried vibrant space-themed artworks by professional artists and members of the astronomy community, and provided an opportunity to see the RAS Bicentennial quilts. The entrance spaces led to a curated Art Room humming with works from professional artists and pieces co-created with local youth groups, alongside the Space Investigators exhibition tracing the North East's astronomical legacy. Throughout the week, there were open public events whilst the conference spaces turned into dynamic learning zones for school groups and teachers, and welcoming spaces for community partners. There were science workshops, careers sessions, poetry, football, storytelling, and unforgettable dance performances. Everywhere you looked, engagement was there – integrated, visible and connected.

The art of co-production

Including communities meant genuine, authentic and meaningful involvement and co-production. Leading up to NAM, the team partnered with community organisations and creatives in collaborations in which young people were treated as equal contributors. As one youth worker reflected, "They were taken seriously, and that changed how they saw themselves".

Groups were actively welcomed with official welcome signs and conference passes bringing particular pride. Participants toured the exhibits, meeting scientists and artists, with familiar faces helping to ease the nerves of first-time visitors to a university, while the professional presentation of their work signalled that it, and they, belonged. Young people's confidence visibly shifted, as one youth worker noted: "You could see their pride grow in real time"; another said: "They all felt valued… their voices mattered." Small moments made big differences, such as one participant who had previously not believed university was for them, sending an emotional audio message after talking with astronomers about the ideas behind their artwork, and later returning with family to see 'their' exhibition. A family member who visited NAM2025 described the experience as "really special; it made us feel part of something big".

Different formats, different publics

At the conference venue, NAM2025's public strand unfolded across three evenings: a fascinating dark-matter lecture by Prof Isobel Hook, a lively 'Three Minutes to Inspire' competition, and a live recording of the *Supermassive* podcast. Around 200 people attended these events, and feedback praised the clarity of the talks, the variety of formats, and the sense of access to research. For several, it was their first experience of an academic setting.

It was important to also include activities within the wider community alongside events at the conference venue. We took the NAM2025 experience to two major regional events: the Big Bang Family Science Fair at Ushaw House and, in a first for Durham University, the Durham Miners' Gala. Meanwhile, award-winning author Richard O'Neill created a brand-new story for NAM2025, celebrating the North East's industrial and astronomical heritage. Performed for families and a school group at Seven Stories' Two Tales pop-up, it offered an opportunity to involve younger audiences. Collectively, these off-site activities extended the reach of NAM2025's engagement to nearly 16 500 people.

Widening participation by design

For longer-term impact, the NAM2025 school programme involved pupils from schools who work with us on existing widening participation and engagement programmes. This included:

- Moorside Primary School pupils participating in 'Bridging the Gap', a project focused on widening pupils' careers awareness, and expanding their science and cultural capital. The year-long project, coordinated by Building Self Belief CIO with support from Point North, involved multiple partners including Durham astronomers.
- Science Ambassadors from Woodham Academy, Chilton Academy, West Rainton Primary and St Oswald's Primary. This programme, supported by Business Durham, sees young people become the ambassadors for science in their communities. The Chilton group filmed interviews with conference delegates for their project creating engaging careers resources to share with their peers.
- Catchgate Primary School, long-standing partners through the award-winning Stargoal football-and-astronomy project, also joined us, including playing a match!

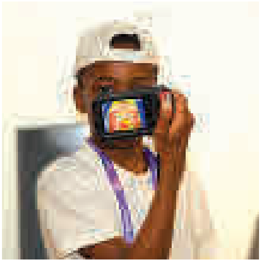
Pupils experienced what it felt like to be part of an international research conference. Many partners supported the schools programme, including curated visits to the 'Space Investigators' exhibition and the Art Room, space-inspired dance workshops with TINArts, filming training with award-winning documentary maker, Carl Joyce, and hands-on activities with Kielder Observatory, Sunderland, Newcastle and Northumbria Universities, and the Royal Astronomical Society.

Feedback shows that this immersive approach was valued by both pupils and teachers, letting everyone feel part of something bigger and increasing awareness of astronomy and career opportunities. As Nic Jenkins, Head of Science at Woodham Academy, reflected: "It's a joy to see our students inspired by the wonders of astronomy and the collaborative spirit that drives scientific progress.

By inviting young minds to engage in a diverse range of hands-on activities and discussions, we're planting the seeds of curiosity and confidence that may one day lead them to make discoveries of their own."

Reigniting the spark

Supported by the Ogden Trust, a group of physics teachers took part in conference sessions and tailored training. Teachers described this as highly motivating and professionally valuable, reigniting their enthusiasm for astronomy. Exposure to cutting-edge science and hands-on demonstrations was especially useful for thinking about how to engage non-specialists, echoing classroom practice. The teachers also appreciated the strong sense of community that they developed. All agreed the experience was inspiring, enriching and directly beneficial to their teaching.



Top tips for integrating community engagement into a conference

- Put community at the centre from the very beginning.
- You can't do it alone! Get a supportive team together, committed to the same principles. Advocate for senior management support and empower people to get involved and contribute.
- Build on long-term relationships. Where is trust already in existence? Get partners involved early so they can also plan early.
- Make the time to plan and be ready to adapt.
- Funding does enable – but what resources/programmes/partners are already there and could be involved?
- Co-produce authentically and value these inputs with professionalism.
- Integrate engagement throughout the conference spaces, and provide opportunities for delegates to be, and feel, involved.
- Showcase local identity and regional strengths – do what works for you and your communities/partners.
- Make the conference welcoming and inclusive, including for community partners – consider their expectations, experience and needs.
- Gather feedback in the moment.
- Celebrate the emotional and personal as well as intellectual impact – remember that those small moments really matter.
- Remember why you're doing it.

Involving delegates

Engagement was deliberately interwoven into the conference spaces and highlighted at every morning welcome session. This made it difficult to ignore with 85% of conference attendees who responded to our survey stating that they were aware of the public engagement activities, and all but one stating that similar programmes should be considered moving forward.

The scientists' art gallery and curation of John Pacey's 'X-Ray Zodiac' artworks took the familiar form of a poster session, turning an unfamiliar activity into a familiar behaviour: people stopped, looked, and chatted as they would around academic posters. Delegates who took part in 'Three Minutes to Inspire' particularly valued the opportunity to contribute to the public programme.

Other spaces, such as the Art Room and Moon Palace, were designed to be inviting, and visiting community groups shared spaces with the conference delegates. In the Art Room, artists Sarah Stamp and Sophie Gwynn curated a lively mixture of digital, musical and visual works by professional and community artists, alongside imaginative 'space bases' crafted by North East primary pupils working with the Centre for Life. Sarah's creative sessions with Little Chefs, Big Chefs community group and Durham astronomers added playful exploratory works and provided additional opportunities for visitors to contribute. The Moon Palace, a mobile observatory and artwork created by Heather Peak and Ivan Morison. Her presence at NAM2025 marked the launch of a collaboration between East Leeds Project, Leeds University, Durham University, the University of Hertfordshire, and Queen Mary University of London. Supported by the Ogden Trust, the programme is supporting scientists in developing interdisciplinary skills and fostering connections between their institutions and local communities.

"We worried about whether delegates would see community participation as a distraction, or whether creative and arts spaces would feel isolating rather than inviting"

Around 100 delegates attended the 'Celestial fingerprints' artwork unveiling. The evening of art and poetry culminated a performance of TINArts inclusive dance company's 'PULSE', produced in collaboration with Durham University. Several delegates described it as the most affecting moment of the week, "breathtaking", while some were even moved to tears.

Several artists arrived wary of scientific spaces and left with new confidence and networks. Being part of NAM2025 conferred professional legitimacy within this science setting, and at least one artist has received invitations to future science conferences. In interviews, artists spoke candidly about having grown up believing that conferences weren't "for people like me", and how the week challenged that narrative.

We worried about whether delegates would see community participation as a distraction, or whether creative and arts spaces would feel isolating rather than inviting. However, the overall effect, noted by several observers, was cultural, normalising engagement for those who wouldn't typically opt in and legitimising it for those that do. Delegates' comments and survey responses were overwhelmingly positively, highlighting not just the potential impact on the communities, but on the culture of academia and their own conference experience.

Lessons we learned

From the outset, we were determined that community should sit at the heart of NAM2025. Our current evaluation suggests that we largely achieved this, while also identifying valuable opportunities to strengthen future work. It was the key elements of senior support, coordination and time that made our approach possible. Durham University is fortunate to have senior leaders who champion engagement and community. This support gives staff and students the trust, time, and freedom to be creative, experimental, and confidently take calculated risks in developing new programmes. We benefit from dedicated teams committed to building sustained, mutually beneficial relationships with community groups, schools and partners.

More than 30 people served on the NAM2025 Local Organising Committee, bringing together PG students, administrative and technical staff, engagement specialists, and academics, including the Head of Physics. Under the empowering leadership of Dave Alexander, we built a shared sense of purpose and determination. Everyone contributed openly across roles, asking questions, offering ideas, and supporting each other. Delivering such a programme requires extensive work, time, and sustained teamwork. With numerous partners involved, strong coordination was essential with regular meetings,

What the delegates said

Elevating the conference experience

"It was great… the best thing about the conference for me."

"I became more engaged and excited as the conference went on, unlike many highly technical or specialised conferences where tiredness accumulates after several days. It was exciting, engaging, inspiring, and full of learning opportunities."

Involving the public

"It makes the conference far more vibrant and engaging, and gives the public a glimpse of what our conferences are like."

Shifting Academic Culture Toward Inclusion and Engagement

"It is really important to not only put on engagement activities for the local community during NAM, but to integrate them into the conference and involve the attendees, because it is important for scientists to be involved in community engagement."

clear communication, and the expertise of experienced event coordinators. We also relied heavily on the goodwill and in-kind support of regional and national partners.

Our two-year planning period proved invaluable. Speaking with previous NAM organisers helped us to understand what worked for them, and to carefully consider what mattered most for Durham. It also gave us time to fully address practicalities including safeguarding, risk assessments and ethics.

With time to plan, we aligned NAM-funded work with existing programmes and identified where additional funding and support was needed. Our regional partners again played a crucial role: by integrating existing funded activities, we created a diverse, vibrant programme that showcased the North East's space-engagement community. Importantly, this allowed our internal teams to focus on coordination rather than delivery during the conference.

Evaluation was part of every programme element, using mixed methods such as surveys, interviews, and graffiti walls. This was complex and required specialist planning, supported by departmental funding for a

Above: **Celestial Fingerprints is a 30-piece installation for Durham's Ogden Centre for Fundamental Physics created by artist-poet Lizzie Lovejoy (pictured). Developed through conversations and workshops with Durham staff and young people from More Stuff Like This Please! (Stockton ARC) and Investing in Children's Art Café (including care-experienced and neurodivergent participants) the piece wove their conversations and art into a striking visual narrative with accompanying poetry.** (All the artwork presented here remains copyright Lizzie Lovejoy)

placement student who implemented evaluation strategies and analysed findings. As ever, gathering high-quality data was challenging, and we recognised the need for better real-time feedback at public events, and the need to ensure feedback is obtained during events.

The run-up to NAM2025 and the week itself was intense. Having a positive, supportive team made all the difference. Tools like the WhatsApp group proved invaluable for last-minute issues. Despite the long days and evenings, we kept in mind that every visiting group was experiencing NAM2025 for the first time, and deserved the same energy and care as those on day one.

We also found some key areas to improve. Future conferences could better integrate engagement activities into the timetable and highlight them more clearly to delegates. It would also be good to consider how to more actively involve delegates from outside the region. Public event attendance was lower than hoped, and better advertising, avoiding clashes with conference socials, and clearer signposting to linked exhibits would help.

Final thoughts

Could the same activities have run as standalone events? Of course. But a conference does two things that are hard to replicate. First, it concentrates expertise, attention and resources: hundreds of people coming together for a short period of time. And for us in the North East, hosting a major event and being able to showcase and celebrate the amazing region both to people living here and to others really matters. Second, it lends legitimacy. When a prestigious meeting puts community on the main stage, it signals to delegates and partners alike that this isn't an add-on, that engagement is part of astronomy's culture and everyone there is valued.

NAM2025 showed us exactly what can happen when community is placed at the very heart of a conference. It created an atmosphere of connection that lifted everyone involved: researchers, young people, artists, teachers, families and community partners. It was hard work, but it was also energising, exciting, and at times, even moving. We loved watching confidence grow, assumptions shift, and new relationships spark. We loved seeing community groups feel at home in a university space, and hearing from delegates about how the community engagement was deepening their experience.

Most of all, we loved being reminded, day after day, why this work matters: because when people meet as equals, share space, and feel valued, something transformative happens. NAM2025 affirmed our belief that conferences can be powerful engines for connection and culture change, and we remain deeply grateful to RAS for the privilege of hosting a meeting that embodied 'science through connection' so fully. It is an experience we will carry with us, and one we hope will inspire future conferences to be equally bold, inclusive and joyful. ●

AUTHORS
This article draws on evaluation work encompassing comments and opinions from community participants, partners, and delegates at NAM2025. It features contributions from members the NAM2025 Engagement Organising Committee, a multi-disciplinary team that includes researchers, public engagement professionals, cultural specialists, event and communications staff and students including James Douglas, Ged Matthews, Gavin Leroy, Zoe Le Conte, Grace Lawrence, Shufei Rowe, Leighton Kitson, Judith Williams, Sophie Gwynn, Vicky Fawcett, Dave Alexander and Lorraine Coghill.

Q&A

Jim Wild, who took over as President of the RAS in May, talks to Indra Bains about his plans for the Society's future

Jim Wild President of the RAS

"In a time of widespread scientific misinformation, being able to explain things clearly and honestly is crucial"

Tell us a bit about who you are and what you do.
I'm a professor of space physics based in the Physics Department at Lancaster University, where I lead the Space and Planetary Physics research group – a team of around 20 academics, postdoctoral researchers and postgraduate students studying the dynamic interactions between the Sun, the Earth and other planetary bodies. My own research areas include the natural space environment, including the aurora borealis, the impact of space weather – such as geomagnetic storms – on technological systems, and interactions between planetary magnetospheres and the interplanetary medium.

What does becoming president of the Royal Astronomical Society mean to you personally and professionally?
It's an absolute privilege. I've been a Fellow of the Society for almost 25 years. In that time, I've served on the Membership Committee and twice on Council, first as a regular councillor and then as a vice president for geophysics. This experience has underlined the responsibilities of the president, so it's an honour to be entrusted with the role. The RAS is a unique and respected organisation, able to speak on behalf of the UK's astronomy and geophysics community with expertise and authority. At a time when the UK research and higher education sectors are under considerable financial pressure, I know the Society has a vital role to play in communicating the contribution of astronomy and geophysics to the UK's scientific and cultural landscape.

Can you tell us about your journey into astronomy, and what first sparked your interest?
As a child, I was obsessed with anything space-related. My dad was a keen photographer, and slide shows of family holidays or day trips were a regular occurrence. One day, a package arrived with a set of mail-order NASA slides featuring highlights of the space race, and that became my firm favourite. I grew up in the post-Apollo era, but I recall many of the space highlights of the 1980s, such as Giotto's encounter with Halley's Comet, the first flight of the Space Shuttle, the Challenger disaster and Voyager 2's encounter with Neptune, usually through coverage on BBC staples including *John Craven's Newsround*, *Tomorrow's World* and *Horizon*. It was a fascination that never wore off.

Were there any key individuals who shaped your career path?
There were many. My PhD supervisor, Tim Yeoman at the University of Leicester, and Farideh Honary, who offered me my first academic job as a lecturer at Lancaster University, both supported me at crucial points in my training and career. But there are dozens of colleagues within the community who have made a massive difference along the way – I've benefitted hugely from their friendship and support across the years.

Your research has contributed significantly to our understanding of space weather. Which pieces of research are you most proud of, and how has the field changed over the course of your career?
Early in my career, I really enjoyed working with ESA's Cluster mission, the first four-spacecraft mission to explore the Earth's magnetosphere. My team and I are still exploiting its 20+ year data set to understand the coupling of the solar wind to the geospace environment. The nature of modern research is that teams of researchers often chip away at different aspects of a problem for years, and I've been lucky to work with a group of fabulously talented students and researchers throughout my career. In the last 15 years or so, the field of space weather has really matured from its solar-terrestrial physics origins, and we are now seeing the benefits of research-to-operations activities that will help society build resilience in the face of space weather events.

Which developments in our understanding of solar-driven impacts do you foresee over the next decade?
One of the biggest challenges in space weather is understanding the factors that influence the geoeffectiveness of space weather events. For example, what is it that means some coronal mass ejections drive much more powerful geomagnetic disturbances than others? Tackling this question will require new measurements in, and better models of, the geospace environment.

To truly understand the impact of space weather events on critical infrastructure, we also need to enhance the feedback loop whereby scientific research is turned into operational tools, and real-world use then feeds back to improve the research, so that both sides continuously evolve. The UK has led the way here with the Space Weather Instrumentation, Measurement, Modelling and Risk (SWIMMR) programme – a UK-wide research initiative focused on space weather. The aim was to take quite fundamental research, such as understanding the Sun–Earth system, and translate it into operational forecasting tools for the Met Office. Building on this Research to Operations (R2O) experience to close the circle and drive forward the science though the so-called R2O2R has the potential to be transformative.

As president, what are your priorities for the RAS?

As of January, the UK astronomy community is facing very significant challenges around the funding that supports its researchers and facilities. I suspect this is going to be an issue that will extend across my term as president. Among the various organisations and stakeholders involved, the RAS is uniquely unconflicted in its ability to advocate for astronomy and space research, and I plan to use this voice to best effect.

Beyond the current funding issues, the Society is beginning to plan improvement works to its Burlington House headquarters. The signing of the new 999-year lease in late 2024 gives us the security to consider changes that will improve access to the building and make it suitable for a range of purposes, starting with the ground-floor space. But, as a Fellow who has never been based within 100 miles of Burlington House, I am clear that we also need to reflect on the benefits of membership for Fellows who are not regularly able to attend meetings in Piccadilly. My aim is to make the advantages of membership such that it becomes a no-brainer for professional astronomers and geophysicists at all career stages to be Fellows of the Society, wherever they are based.

How can the RAS, given its size and focus, maximise its impact in policy, education and public engagement?

The Society is a lean organisation, employing about 20 staff in total. Using that metric, the Institute of Physics is more than 20 times its size, so has significantly more capacity to promote physics, but must represent a much broader set of disciplines. One of the RAS's strengths is its ability to focus entirely on astronomy and geophysics. Given its scale, the impact we have across areas including policy, research, education and outreach is remarkable. To multiply this impact, however, we need to harness the power of the Fellowship.

Advocating for our research means engaging different audiences appropriately, whether school children, policymakers or the media. That can be daunting, as it takes us outside the comfort zone of communicating with our peers. Some people find that challenge appealing, while others are hesitant. I'd like to explore how the Society can support Fellows in building the skills to confidently make the case to non-scientific audiences – for example, through media or policy engagement training. This also brings us back to the Society reflecting on the full package of membership benefits available to the Fellowship.

You were awarded the RAS James Dungey Lectureship in 2018 in recognition of your public communication of science. What responsibility do scientists have to communicate their work to the public?

Most of us are funded from the public purse, so we have a responsibility to communicate our work to non-specialist audiences. I also think it's important because, beyond the enthusiasts, astronomy and geophysics can feel quite abstract or distant from everyday life, especially in these uncertain times. Good communication helps bridge that gap, showing how our work connects to areas like technology and climate science, drives innovation and skills, and broadens understanding of our place in the universe.

In a time of widespread scientific misinformation, being able to explain things clearly and honestly – including uncertainties – is crucial. So for me, communication is part of the job. It's about accountability, but also about inspiring people and ensuring the value of what we do is actually understood beyond the scientific community.

What still excites you about astronomy after all this time?

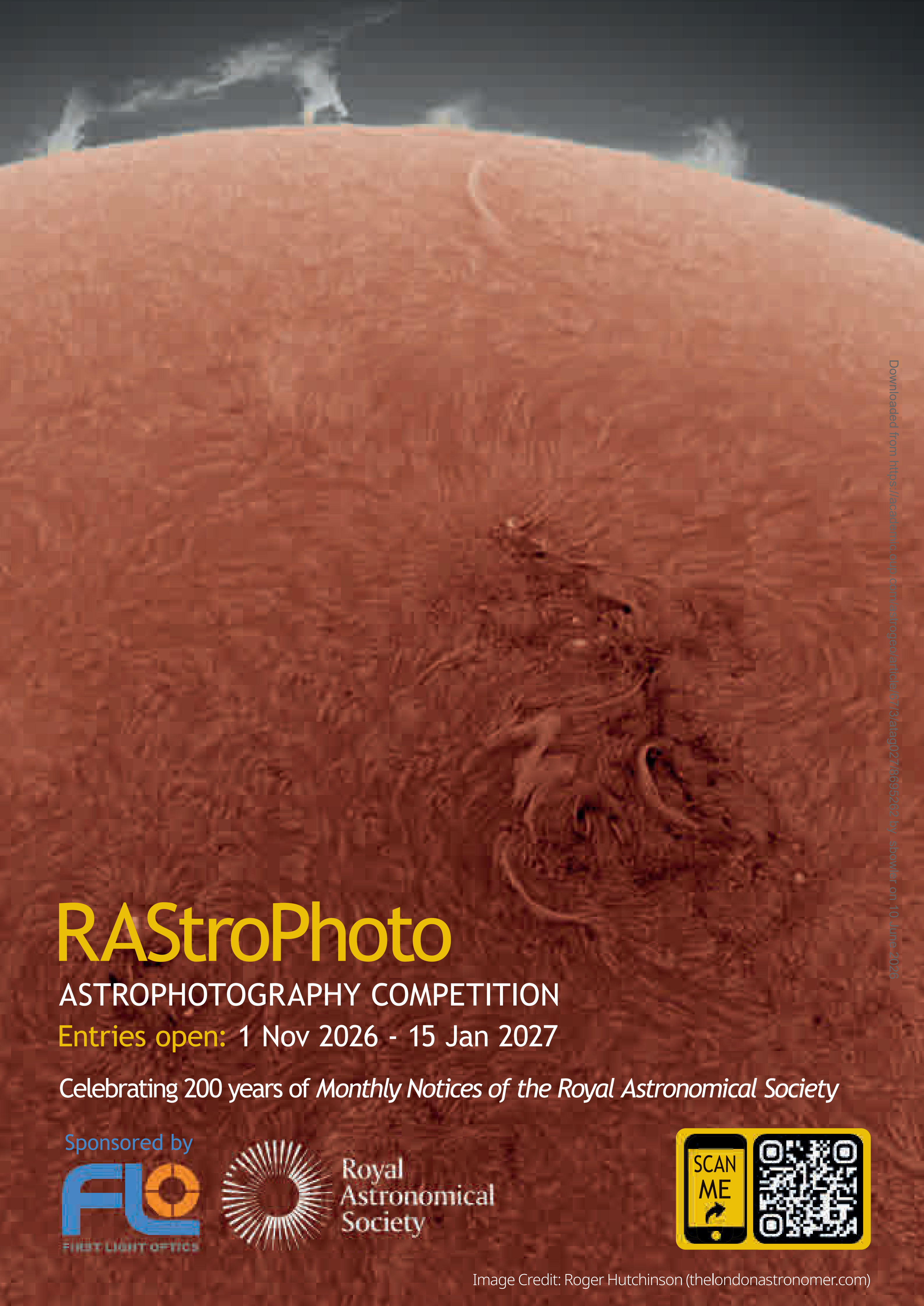
It's the combination of curiosity and relevance that keeps it exciting. On one hand, we're still trying to understand a system we don't fully grasp: the Sun-Earth connection is incredibly complex, and there are always new observations that challenge what we think we know. At the same time, it's not just abstract – the space weather processes we're studying affect things people rely on every day, like satellites and power grids. I find it really motivating that what might start as quite fundamental physics can end up having very real-world consequences. I also really enjoy those moments when something doesn't quite fit expectations: it forces you to rethink things rather than just apply what you already know. More broadly, there's still that underlying sense of curiosity, trying to understand how the space environment around Earth works, and how it connects to the wider universe.

How do you spend your free time?

I'm an enthusiastic fell runner and can often be found in the hills and mountains of the Lake District, the Howgills and the Yorkshire Dales. Since taking it up in 2015, I've tended to focus on ultra-distance events, mainly because what I lack in speed I make up for in bloody-mindedness. It's a very social sport, and you can find yourself running alongside folks from all walks of life. Navigating through a couple of miles of bog before ascending some of the highest peaks in the country is a great leveller! ●

"I find it really motivating that what might start as quite fundamental physics can end up having very real-world consequences"

AUTHOR
Indra Bains is editor of *A&G*.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