

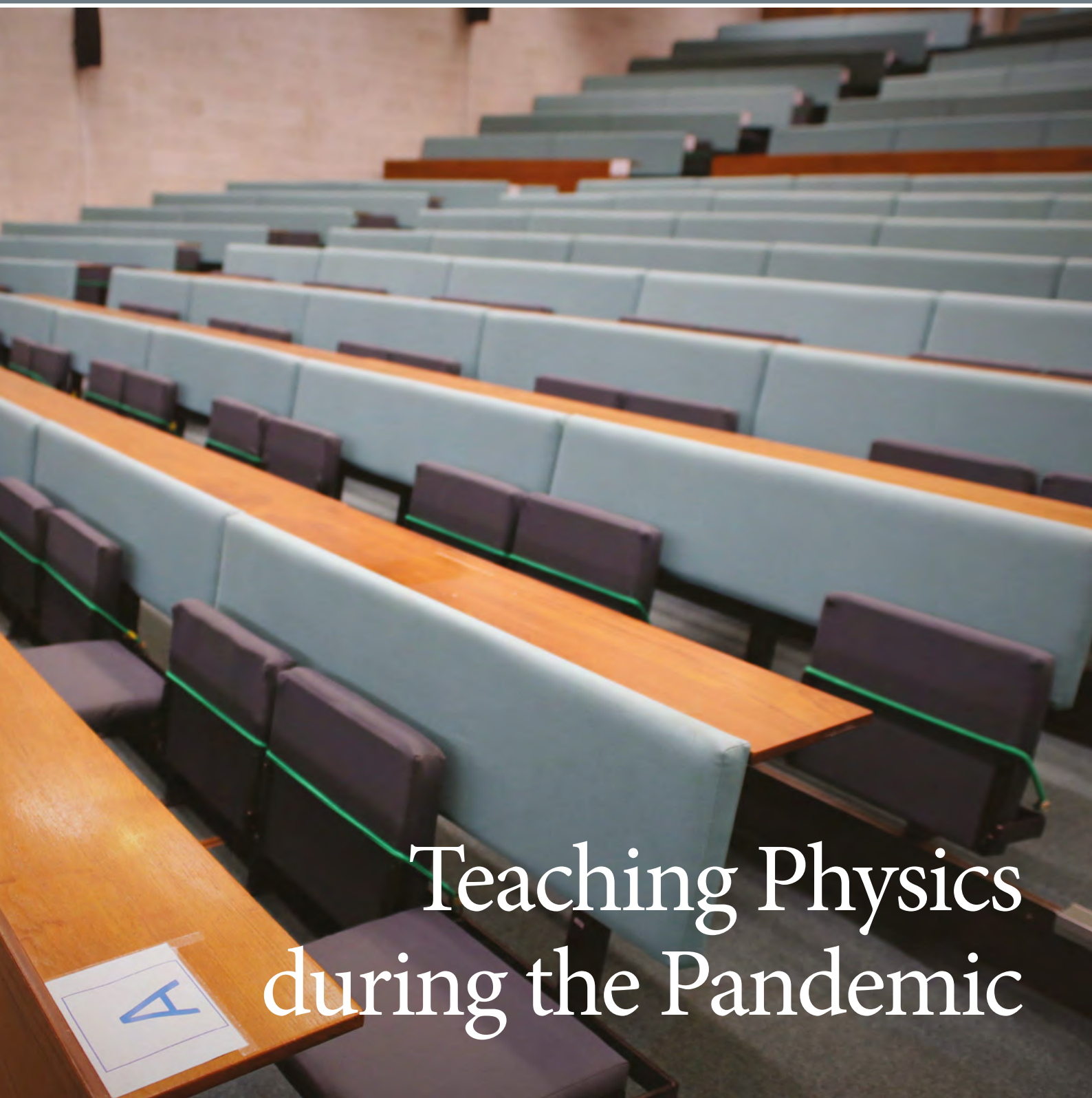


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News from the Cavendish Laboratory



Teaching Physics during the Pandemic

EDITORIAL

2020–2021 was a truly demanding academic year for all of us. While the constraints on experimental research were difficult enough, those on maintaining the undergraduate teaching programme were even more complex and demanding. Ulrich Schneider in his guest editorial describes how the teaching was realigned against almost insuperable odds. Ulrich rightly praises all the teaching administration, technical and support staff, as well as the lecturers, for their dedication. What he does not mention is his own outstanding leadership of the team who had to implement the new regime imaginatively in an incredibly short time. We are all profoundly grateful.

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The Pippard lecture theatre seating arrangements to ensure social distancing.



Guest Editorial

Teaching Physics during the Pandemic

One of the most challenging tasks we have ever faced has been to maintain the highest quality teaching in the face of the COVID pandemic, the resulting lockdowns, and the constantly changing government and University instructions. ULRICH SCHNEIDER, Director of Undergraduate Education in the Cavendish, describes how the Department responded to a quite unprecedented teaching and examining challenge.

In March 2020, the University was suddenly faced with the unprecedented requirement to close its buildings. This was a particularly challenging instruction for the Cavendish Laboratory with its emphasis upon research and training in Experimental Physics. It created major difficulties for everyone, experimental groups having to abandon experiments and shut everything down with only a few days' notice. While every effort was made to come up with a *modus vivendi* which enabled experimental work to continue, it is important to recognise that the shutdown created severe difficulties for many MPhil and PhD students and Postdocs on time-limited studentships and projects.

Equally demanding was the impact of the pandemic on our undergraduate teaching programme. The timing of the lockdown, announced in March 2020, was rather fortunate, as the lab closed after the end of Lent term when almost all undergraduate students had already left Cambridge. This gave us a few weeks to restructure teaching formats for Easter term 2020 and to develop new formats for the upcoming examinations.

We were delighted and impressed by the positive response of everyone involved in the undergraduate teaching programme. The new arrangements were particularly demanding for colleagues who lectured

in the Easter term 2020. They had only a few weeks to prepare recordings of their lectures rather than giving them live. And anyone who has ever tried to pre-record their lectures can appreciate what a daunting task this is. Not only do we normally rely on the direct nonverbal feedback and involvement of a student audience and the energy we receive this way, but it is also far from trivial to lecture engagingly and spontaneously knowing that every little pause and stutter is now recorded for posterity. The recorded lectures were available to the students long after they were first recorded, which they much appreciated. Most lecturers accordingly found that lecture preparation and recording took very much longer than preparing and delivering them in the traditional manner.

The examinations were a particular challenge. The Physics examinations are a highly fine-tuned and complex operation which builds upon many years of experience. Any potential changes are normally scrutinised for at least the better part of a year, taking account of every complexity imaginable. Now, suddenly, we were faced with the need to rethink everything and come up with a rather different approach within a few weeks.

We quickly realised that normal written assessments would not be fair, as students would take the exams at home in potentially hugely varying circumstances. Therefore, the decision was taken that all first-, second- and third-year students (Parts IA, IB and II respectively) would be allowed to progress to the next year and the written exams were turned into 'formative assessment', intended as an opportunity for feedback that would not be recorded in the student's record. But there was a particular challenge for those third year (Part II) students that wanted to graduate after three years and who needed a classed degree. These students were all assessed by a series of video oral vivas.

Our memories of the 2020-2021 academic year centred on the frequently changing guidelines that evolved as more was learned about the virus and as the pandemic and the government's position developed in sometimes unexpected ways. It is probably not unfair to say that no-one would describe the governance processes of the University as particularly agile. In a normal year, teaching and assessment runs almost on 'autopilot'. It follows the best practices that have been developed and tested over many years and have resulted in high quality teaching and assessment. Any proposed change, even if it appears to be very

benign, must be scrutinized on many levels as there are so many possible combinations of unique factors that could lead to unintended and unfair outcomes. This gives a glimpse of the enormity of the task that was forced upon us by the very agile and fast-changing nature of the pandemic and even more of the political response.

We were able to reconfigure totally the IB practical classes for Michaelmas 2020 and ended up being one of the very few departments that enabled all their second- and third-year students to have all their normal practical sessions during the Michaelmas term. In the Lent term, when students were not allowed to return to the University at all, all part III students and project supervisors had to restructure their projects so that they could work without access to physical equipment. In IB, we took the opportunity to roll out a new course on Research Skills that required the students to produce their first scientific papers, posters and presentations on scientific topics and was met with largely enthusiastic responses.

We also had to reinvent examining yet again to provide fully invigilated Part III exams online. Together with Mathematics, our department took part in a pilot programme in early Lent 2021 that enabled the University to roll out online proctoring more widely during the Easter Term 2021 examinations.

We are now starting the new academic year 2021–22 with a far more optimistic outlook, expecting that the vaccines will enable us to provide most of our teaching back in person – even though many safety measures will remain (see front cover). No doubt, the pandemic will continue to provide twists and turns along the way, but one of the main lessons from the past 18 months is how resilient and agile we can be if needed. At the same time, many of us are still exhausted, and we will need to ensure that we can recover before the next storm.

We owe a huge debt of gratitude to the enormous efforts made by everyone to keep the show on the road, both in their teaching and examining responsibilities, during a quite unprecedented set of circumstances. I am especially indebted to the enormous efforts of the teaching administration and all technical and support staff, that enabled us to implement all necessary changes as and when they came and to provide the best possible education for our students during this most challenging of times.

Manufacturing metre-sized gratings with nanometre precision

A team led by **DAVID BUSCHER**, **CHRIS HANIFF** and **JOHN YOUNG** of the **Cavendish Astrophysics Group** has been awarded a £900k EPSRC grant to develop a new precision manufacturing process based on technology developed by the team to equalise the optical paths in arrays of telescopes. This technology will address a need in astronomy for metre-scale diffraction gratings; in the longer term it could bring about a revolution in precision manufacturing.

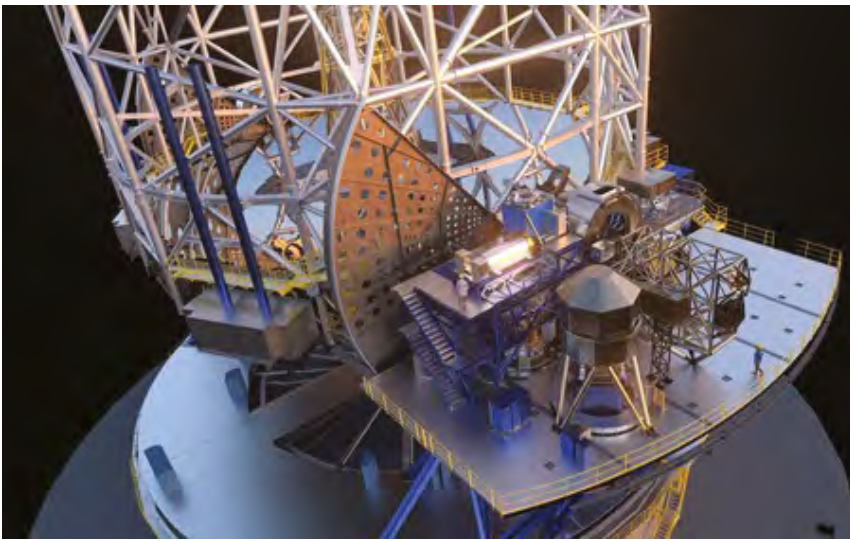


FIG 1 (above): Artist's impression of the E-ELT. The primary mirror is 39 metres in size, the image showing the platform where large spectrographs will be located. Note the size of the people in the picture for scale. Credit: ESO/L. Calçada

FIG 2 (opposite, top-left): One of the largest astronomical diffraction gratings currently in existence. This grating is 840mm in length, consisting of two 420mm-long sub-gratings; gratings more than 1.2 metres in size are needed for the upcoming generation of large telescopes. The plexiglass protective cover shown in the picture is removed in operation. Image courtesy of Samantha Thompson - HARPS3 Echelle.

Over the past 25 years, precision manufacturing has become a core technology enabling the market growth of thousands of products. Smartphones, digital imagers, and even medical implants depend upon precision manufacturing with tolerances at the micron or sub-micron level. While tolerances at the nanometre level are possible using techniques such as electron-beam lithography, these tolerances can usually only be maintained over distances measured in millimetres. This new initiative aims to push manufacturing technology so that nanometre precision can be maintained over metre scales.

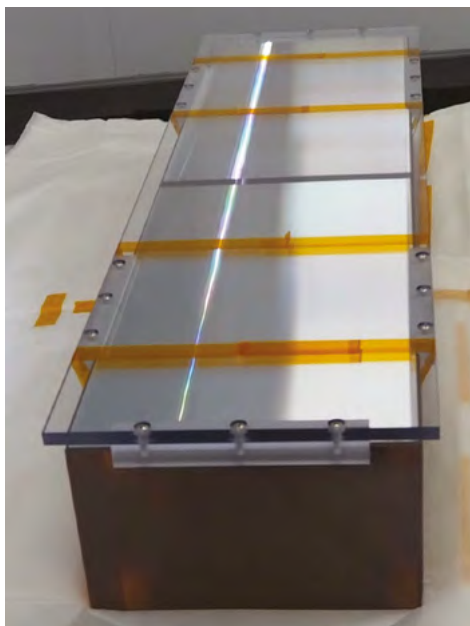
The impetus to develop this technique came from the needs of spectroscopy on Extremely Large Telescopes (ELTs) such as the European ELT (Ref. 1 and Fig. 1).

Spectrographs are workhorse instruments for understanding all kinds of astrophysical processes.

They depend upon the use of diffraction gratings to split light into multiple spectral channels. These gratings consist of parallel finely-spaced grooves manufactured to very high precision: cyclic errors in the groove positions at the level of 1 nanometre can cause 'ghost' spectral lines to appear. The overall size of the grating scales with telescope diameter, and for the upcoming generation of astronomical telescopes with primary mirror diameters of tens of metres, the gratings needed are typically metres in size (Fig. 2).

To solve the manufacturing challenge of nanometre precision over metre scales requires a combination of two new technologies. The first is that of manufacturing nanostructures in silicon using wet etching. This has been used by groups such as Uwe Zeitner's group (2) at the Fraunhofer Institute in Jena to make centimetre-sized silicon gratings with exquisite accuracy (Fig. 3).

The second technology is based on the delay lines developed by the Cavendish Astrophysics team for use in optical interferometers such as the Magdalena Ridge Observatory Interferometer (3). Optical interferometers are the optical equivalent of the radio interferometers pioneered by Martin Ryle and others in Cambridge: they combine the light from multiple telescopes to observe astronomical targets at scales much finer than is possible using conventional telescopes such as the Hubble Space Telescope. The delay lines are used to equalise the optical paths between telescopes in the array and are effectively 'optical trombones', where the moving element, a retroreflecting mirror, must be positioned with nanometre accuracy over a travel of hundreds of metres. This is achieved by mounting the retroreflector on flexures attached to a motorised



trolley and controlling its overall position precisely using laser metrology and coupled servo loops (Fig. 4).

The technology from the MROI delay lines will be used to build a precision 'lithography engine', capable of patterning silicon substrates over metre scales with nanometre precisions (Fig.5). The lithography engine will 'write' patterns on to photoresist-coated silicon wafers using a 'floating head' controlled using very similar techniques as used in the MROI delay lines. The patterned silicon will then be processed by Zeitner's group to yield large, accurate gratings.

The technologies developed here will be used in the shorter term to address an immediate need in astronomy for

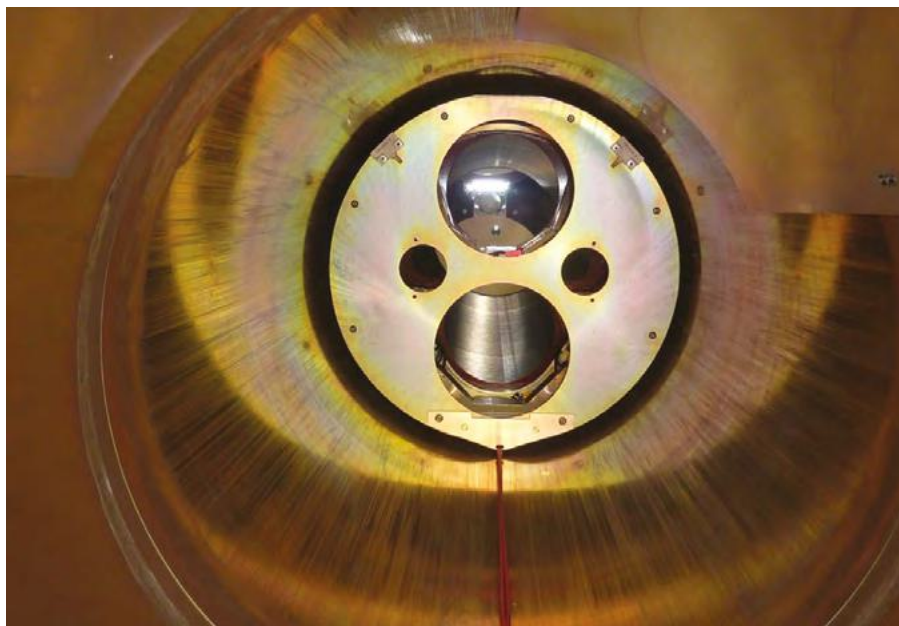


FIG 3 (below-left): Electron micrograph of a portion of a silicon grating produced by Uwe Zeitner's group in Jena. Note the nanometre-smooth blaze facets (the portion of the grooves responsible for reflecting light) produced by wet etching of silicon. Courtesy of U.D. Zeitner, Fraunhofer IOF Jena, Germany

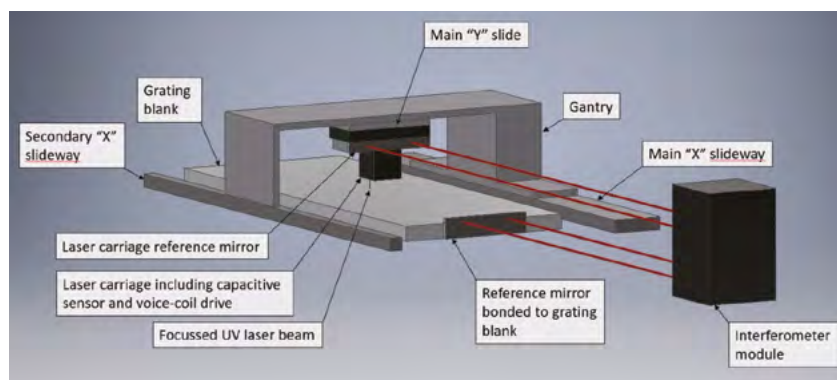
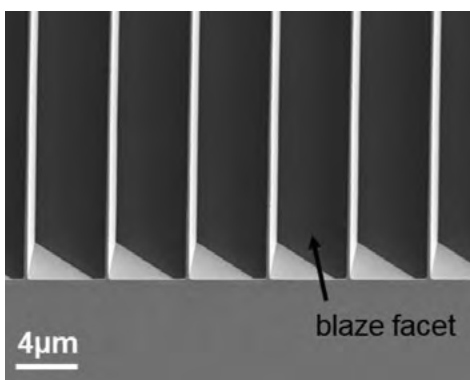
FIG 4 (above-right): The MROI delay line trolley inside its vacuum pipe - view looking through the top port-hole at the retroreflecting mirror. The trolley can travel over 100 metres while maintaining better than 5 nanometre precision in the position of the mirror. Credit: Bodie Seneta, Cavendish Astrophysics Group.

FIG 5 (below-right): Concept sketch for a lithography engine based on our delay line technology. Credit: James Luis

metre-scale diffraction gratings, but the lithography engine can serve as the basis of a more widespread revolution in precision manufacturing. Unlike other grating-patterning technologies which project stripe-shaped interference patterns onto a substrate, the new lithography engine architecture can be straightforwardly extended to allow arbitrary two-dimensional patterning over metre scales while maintaining nanometre-level accuracy. Exploring the manufacturing applications of such an extended capability is the longer-term goal of the programme.

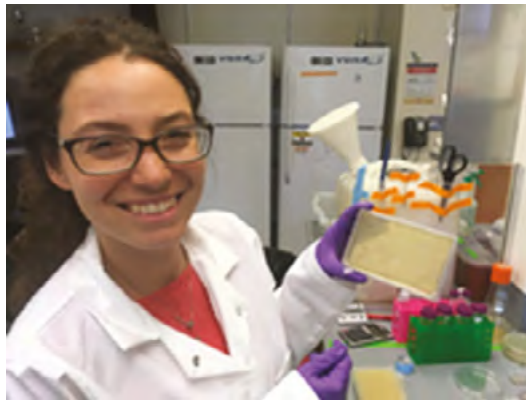
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Watching a virus expand in bacterial colonies offers a new perspective on the adaptability of viruses

DIANA FUSCO describes new research into the processes by which populations expand in space and invade virgin territory, known technically as spatial range expansions. These are ubiquitous in nature, ranging from bacterial biofilms colonising prosthetic implants to invasive species overrunning a continent.

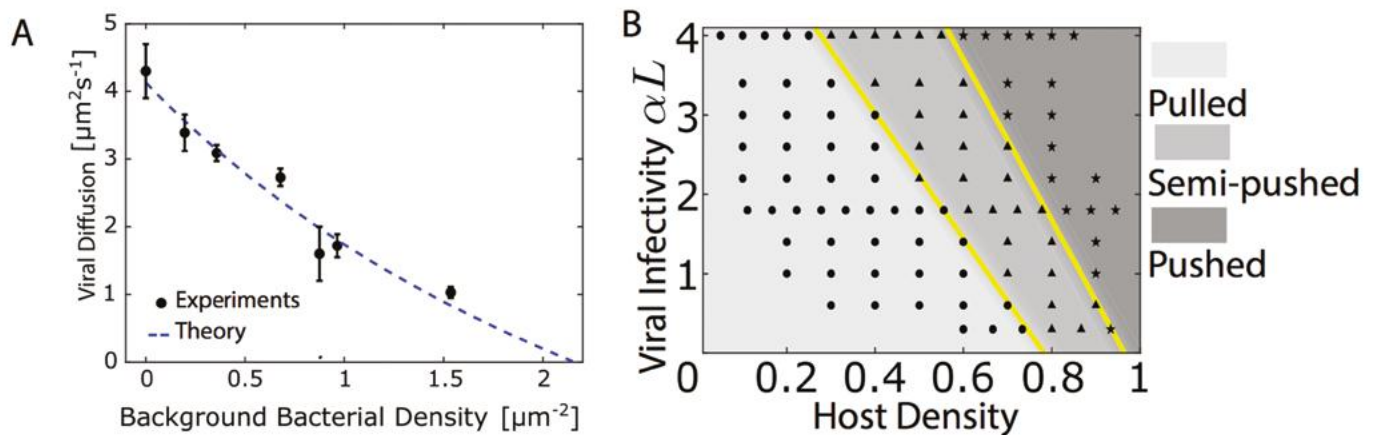


The evolutionary dynamics of these populations, in particular their ability to retain genetic diversity and adapt to new environments, strongly depends upon the type of expansion, which is traditionally divided into two classes. *Pulled expansions* are dominated by *pioneering individuals* at the very front, which have access to abundant resources and, consequently, are more likely to generate the next generation of pioneers in a self-perpetuating loop. Because only few individuals contribute to each generation, the corresponding populations lose diversity very quickly and can easily accumulate deleterious mutations in a phenomenon called *expansion load*. By contrast, *pushed expansions* require high population density to advance, as the individuals grow or disperse more effectively when other individuals are close by, as a result of division of labour, production of common goods, or other cooperative mechanisms. The pushed expansions resemble the breaking of an advancing sea wave when meeting the sand gradient at the sea shore: the front slows down allowing the rest of

the population to catch up creating a mixed front that retains genetic diversity for much longer. Because many individuals contribute to the expansion, deleterious mutations are more easily purged and beneficial mutations can spread more easily, generating a more resilient and adaptable population.

Viruses also spread and evolve in a spatially distributed host population, whether it is a bacterial biofilm or a world of cities and towns, but which expansion best describes them and under what conditions was, until recently, unknown. Since explicit cooperative mechanisms among viruses are rare, the current hypothesis assumed that a pulled expansion was more likely. Using a laboratory model ecosystem of bacteria and their infecting viruses, the bacteriophages (or phages), and a corresponding numerical model, we recently demonstrated that, contrary to current belief, pushed waves occur in viral expansions even if no explicit cooperation exists.

The transition from pulled to pushed expansions arises spontaneously from the feedback between the virus and the host dynamics: as the viral expansion proceeds, infected cells lyse, meaning break up, which inevitably generates a gradient in host density where the susceptible host is depleted in the bulk of the viral expansion. While this gradient in host density promotes viral replication at the front of the expansion as more host cells are available for infection, it also facilitates viral dispersal in the back, as cells hinder viral diffusion due to volume-excluded interactions (fig. 1A). By accommodating this effect in numerical simulations, we showed that pushed waves are expected at high host



densities, typically those used in phage experiments (fig. 1B).

Remarkably, by introducing different variants to the model, we also identified a second mechanism that independently leads to a transition to pushed expansions at large infection rates and incubation times. As viruses cannot disperse while infecting a host cell, the higher the host density the more virus is trapped inside the host and so unable to diffuse. As a result, a second indirect density-dependent diffusion emerges, which leads to a similar phenomenology as described above, albeit triggered by the presence of an incubation time rather than steric interactions (fig. 2). Importantly, this scenario is applicable even if the host environment is not very crowded, and is thus relevant to a wide range of viruses infecting cellular tissues. A schematic diagram illustrating this process is shown in Fig. 3.

Our results point to the phage-bacteria system as a highly controllable platform for investigating experimentally the dynamics of expanding populations with density-dependent dispersal. Beyond phages, our findings show that viral expansions can retain genetic diversity much longer than previously thought, suggesting that viral populations expanding in an infected organism may be very adaptable to changes in the environment. This realization will help build better models for viral growth and evolution in infected tissues and organisms.

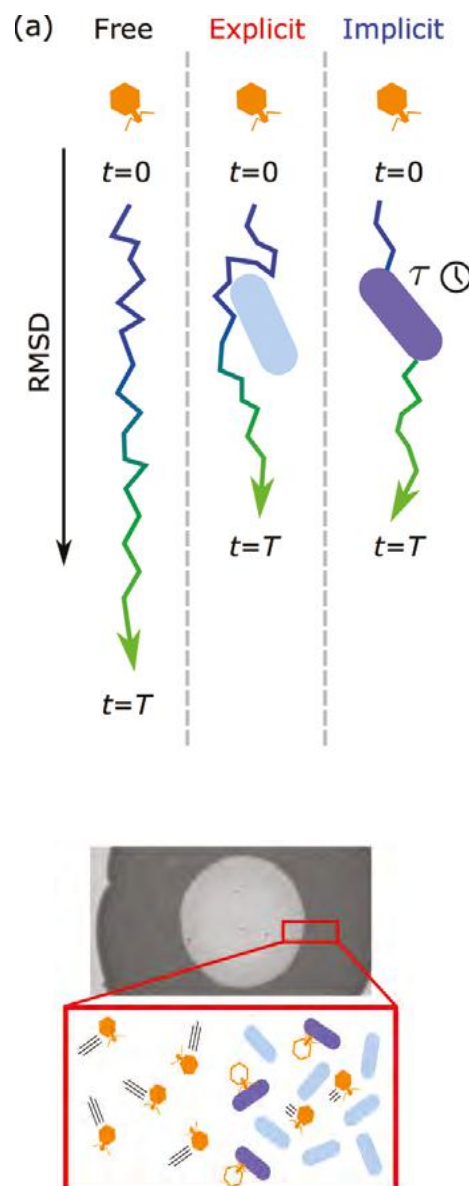


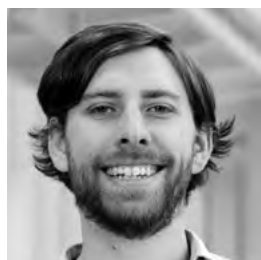
FIG 1 A (above): First-passage time experiments are used to quantify the reduction in phage diffusion as a function of host bacterial density due to steric interactions. **B:** By introducing density dependent diffusion in a PDE model, we identified regions of parameter space where viral expansions are pulled, pushed, or in between.

FIG 2. Pictorial representation of the two mechanisms that hinder viral diffusion in a density-dependent fashion. The explicit effect is triggered by steric interactions, while the implicit is a consequence of viral incubation time.

FIG. 3. A phage plaque (light grey) expanding into a bacterial lawn (dark grey). The bacterial profile emerging at the front of the viral expansion leads to a fast-diffusing phage in the back and slow diffusing phage at the front, giving rise to the population growing, overall, as a pushed wave.

Through the nano hole: Lego technique reveals the physics of DNA transport through nanopores

A new technique established by **ULRICH KEYSER'S** group with collaborators at the University of Massachusetts reveals the fundamental physics of how a polymer such as DNA can thread its way through holes 10,000 times smaller than the width of a human hair.



From the top: Ulrich Keyser,
Kaikai Chen and Nicholas Bell.

In 1953 James Watson and Francis Crick realised that the genetic information is stored in two polymers wrapped around each other in the double-helix structure of DNA, held together by the famous Watson-Crick base pairing. Each base pair consists of two nucleotides on the opposing strands that can be designed to bind. Polymers like DNA are long, chain-like molecules that are found everywhere in biology. Cells exchange information by the transport of DNA through their surrounding membranes pierced by membrane proteins. Some of these proteins are known as 'nanopores' and DNA polymers must pass through these nanometre-sized holes, as demonstrated in the artist's impression in Fig. 1. The transport through nanopores is ubiquitous in biology, the transport of RNA and DNA often involving passage through tight confinement.

About 30 years ago, it was discovered that nanopores are small enough to allow only a single polymer to pass, and the structure, and hence its genetic information, can be read in sequential order. In biotechnological applications, we drive the DNA transport through the nanopores using electric fields acting on the charges of the polymer. The electric field also drives an ionic current through the nanopore which reveals information about the molecular structure of the passing molecules. This process underlies a rapidly developing method for analysing and sequencing DNA called nanopore sensing. At the moment the process of reading the sequence of the DNA relies on the use of molecular motors that slow down the DNA sufficiently to allow reading of the sequence. However, the molecular motors only make steps every few milliseconds which limits the read-out speeds.

If we can avoid the use of these molecular motors, the reading speed could be greatly increased. To achieve this goal we need a quantitative understanding of the physics of DNA molecules

driven through a nanopore. The quantitative understanding requires direct measurement of the velocity of the DNA molecules. The velocity of the polymer depends on the initial configuration and the Brownian fluctuations. As a result of the unavoidable fluctuations, theorists had predicted that the velocity of the polymer is non-linear, also because the driving force is out of equilibrium. A number of models in the literature describe the velocity fluctuations of driven DNA but experimental data to test these models have been so far lacking.

In our study, published in *Nature Physics* [1], we present the first direct experimental and quantitative demonstration of two-stage behaviour in strongly driven polymer transport through



FIG 1: Artist's impression of DNA molecules passing through a nanopore.

nanopores: a slow velocity decrease in the first stage and a significant velocity increase at the end of the translocation. The Cavendish-led team identified the so-called 'tension propagation' theory in the nanopore transport process. Surprisingly, tension propagation is followed by a phase that is described by a 'tail retraction' phenomenon that accelerates the polymer.

To achieve insight into the velocity variations during polymer transport, we employed a LEGO-like technique for assembling DNA molecules that have protruding bumps at specific locations along their length. Spaced at well-defined distances on the DNA, the bumps indicate the translocation time of each segment and hence the velocity of each molecule is revealed with microsecond time resolution. By passing identical copies of the DNA through a nanopore and analysing simultaneous changes in the pattern of ion flow, we determined how the velocity of individual molecules changes. Combining thousands of these translocations revealed the stochastic nature of the process and averaging shows that all molecules behave roughly in the same way.

The experimental results shown in Fig. 2 have thus revealed the two-step process in which the DNA molecules initially slow down before accelerating close to the end of the translocation. Simulations performed by our collaborators at the University of Massachusetts also demonstrated this two-stage process and helped reveal that the underlying physics of the process is determined by changing friction between the DNA and surrounding fluid.

'Our method for assembling LEGO-like molecular DNA rulers has given new insight into the process of threading polymers through incredibly small holes just a few nanometres in size. The combination of both experiments and simulations have revealed a comprehensive picture of the underlying physics of this process and will aid the development of nanopore-based biosensors. It is very exciting that we can now measure and understand these molecular processes in such minute detail.'

Nicholas Bell

'These results will help improve the accuracy of nanopore sensors in their various applications, for instance in localising specific sequences on DNA with nanometer accuracy, [2] or detecting diseases early through target RNA detection. The superior resolution in analysing molecules passing through nanopores will also allow for low-error decoding of digital information stored on DNA. We are exploring and improving the utility of nanopore sensors for their applications in DNA/RNA sequence detection, DNA data storage and DNA sequence mapping.'

Kaikai Chen

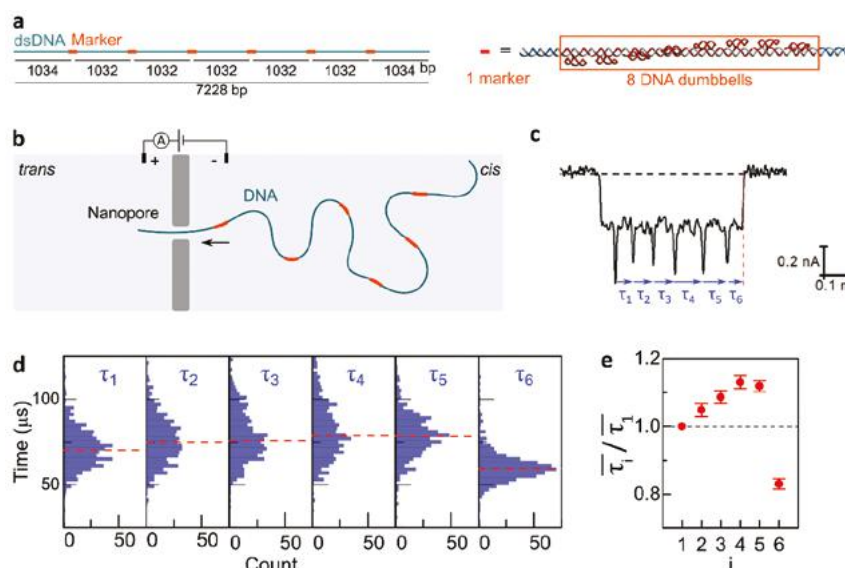


FIG 2: Schematic diagrams and results of the measurement of DNA translocation velocity through nanopores using assembled DNA molecules that have protruding bumps. a. Outline of the DNA construct showing positions of markers along the backbone and the 3D structure of each marker. Each marker comprises eight DNA dumbbells along the dsDNA strand. b. Schematic diagram of DNA translocation through a nanopore driven by an applied electric field. c. Example of an ionic current recording showing a single translocation through a nanopore, with spikes showing the positional markers. d. Histograms of the translocation time between the markers. e. Results of normalized mean time calculated from a Gaussian fit to the histograms showing the velocity change.

This work was supported by an ERC consolidator grant (no. 647144) led by Ulrich Keyser.

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Cambridge Harding Symposium: Quantum Sensors for Fundamental Physics

On Friday 17 September 2021, DAVID HARDING kindly hosted a meeting at Woodlands House on the topic 'Quantum Sensors for Fundamental Physics'. This was a continuation of the very successful series of annual Winton Symposia, but concentrating on a single theme of special interest to members of the Laboratory and also involving a number of our collaborators.

It quickly became apparent that this initiative brought together physicists working in what at first sight appeared to be quite separate disciplines, but which come together in exploiting the capabilities of the coming generation of quantum detectors for particle physics, gravitational wave astronomy and ultra-low temperature physics. In addition, these demanding experiments will give us deeper understandings of foundational problems in quantum mechanics.



The programme began with a description of the very wide scope of the government's initiative by a UK coordinator of this major programme, **Kai Bongs** (University of Birmingham). He described the government's intention of taking a world-lead in the commercial applications of the new quantum

technologies. Worldwide, about £20b is being invested in quantum technologies. In the UK, the total amounts to about £1b and involves over 75 companies. The *Quantum Technologies for Fundamental Physics* programme, part of the national effort, consists of seven major initiatives and has received over £40m for projects. Kai runs the UK Quantum Technology Hub for Sensors and Timing and described the huge range of applications of these new technologies, in particular, the many synergies with projects in the area of Quantum Technologies for Fundamental Physics and the translation of these to other disciplines.



Within the Quantum Technologies for Fundamental Physics programme, there are seven major projects. **John Ellis** (King's College, London) described how all of them can contribute to fundamental issues in particles physics and in gravitational wave detection.

Among the many objectives is the search for ultra-light dark matter, including axion-like particles, with masses in a vast range of energies from 10^{-22} to 10^{-3} eV – these are candidates for the dark matter which dominates the dynamics of galaxies and larger scale structures in the



Colm Caulfield, Head of the Department of Applied mathematics and Theoretical Physics (DAMTP), Cambridge introduces Val Gibson, who described the AION project, in the conference marquee.

Universe. The Laboratory's programme includes work packages in quantum sensors and simulations, and includes a major effort centred on the *Atom Interferometric Observatory and Network* (AION), which will search for ultra-light dark matter and explore fundamental questions in quantum and gravitational wave physics. John also discussed the possibilities of studying phase transitions in the early Universe and probing cosmic strings by searching for a primordial background of gravitational waves. A 'Beyond LISA' space programme involving a Cold Atom Interferometer in Space was a long-term future possibility.



The AION programme was described in CavMag25 (pages 18-19) and the story was brought up to date by **Val Gibson** and Ulrich Schneider. Val described how the programme is already underway, having started in February 2021. Val is a key member of both the AION project and the MAGIS¹ experiment in the US,

which will be ultimately networked to gain maximum sensitivity to detect the classical coherent waves of ultra-light dark matter. Some of her insights about the project are illuminating. For the gravitational wave aspects of the project, AION and MAGIS

will operate in the frequency band of milliHertz to a few Hertz, spanning the gap between the LIGO-VIRGO-KARGA² experiments and the LISA³ space project. Technologically, the AION and MAGIS projects use strontium atomic clocks, which have an extraordinary long term stability of one part in 10^{18} and a large energy gap between the energy levels of the strontium atom. Noise limits the sensitivity of AION – leading contributors are those associated with the Coriolis force acting on the atoms, laser wavefront noise, seismic waves and gravitational gradient noise, all very significant challenges.



Then, there is the problem of squeezing together 10^6 strontium atoms. **Ulrich Schneider** went into more detail on why the experiments have to be carried out at picokelvin temperatures in order to prevent the squeezed atoms dispersing during the time of flight of about 2 seconds in the Earth's

gravitational field. This involves many technologies already being used by Ulrich and colleagues in the Atomic Mesoscopic and Optical Physics group (AMOP). The key to reaching these extremely low temperatures is to use lasers, which may seem paradoxical. The trick is to decelerate the atoms in collisions with the laser beam in three-dimensions and select the coolest of them.



The final talk was by **Silke Weinfurter** (Nottingham University) who described remarkable experiments involved in the construction of quantum simulators for fundamental physics. The interplay between quantum mechanics and general relativity results in phenomena which are difficult or impossible to

replicate in laboratory experiments. These processes can, however, be studied using analogue classical/quantum simulators which enable a wide range of elusive physical phenomena to be studied in a controlled laboratory setting. Three examples of challenging phenomena at the forefront of current physics include analogues for: (1) Hawking radiation which combines black hole physics and quantum field theory, (2) rotating black holes, super-radiance and the Penrose process and (3) the quantum vacuum, its decay from the false vacuum state and the Unruh effect. Other experiments simulate the ring-down of black hole coalescence.

The presentations were followed by a round table discussion on the issues raised, future applications and the wider significance of the Quantum Sensors programme. The distinguished panel included **Mete Atature** (Cavendish), **Alessandra Buonanno** (Max Planck Institute for Gravitational Physics), **Ruth Gregory** (King's College, London), **Peter Knight** (National Physical Laboratory and Imperial College) and **Chris Reynolds** (Institute of Astronomy, Cambridge).



The closing discussion with (left to right): Ruth Gregory, Chris Reynolds, Peter Knight, Mete Atature, and Alessandra Buonanno.

The discussion was indeed wide ranging. Some of the memorable contributions included the following:

- There are many new technologies to come out of LIGO and its successors.
- There are many healthcare applications of quantum sensors.
- Quantum computing is coming. Already, in specialised applications, these processes far outstrip conventional computation. This development will be transformative.
- We do not yet know the magic ingredient which will truly revolutionise quantum sensors and their applications
- We welcome strongly the disruptive potential of confronting theory with experiment. Where do things break down? Do we have the correct tool-box?
- There are major advances to be made in space navigation and tests of general relativity.
- There is strong support from the European Space Agency (ESA) to develop the technology for a cold atoms in space programme for the exploration of fundamental science questions.
- We must be careful about using climate change as a tool in our armoury. Much is beginning to happen, but we are not there yet.
- We need more people working in these areas and must encourage more international collaboration.
- We must preserve curiosity-driven research and maximise the strength of our position internationally.
- A key need is people and the necessary support for them to undertake unconventional interdisciplinary research that befits the Quantum Technology for Fundamental Physics programme.

1. Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS)
2. Laser Interferometer Gravitational-wave Observatory (LISA), French-Italian Gravitational Wave Detector (Virgo), Kamioka Gravitational Wave Detector (KAGRA).
3. Laser Interferometer Space Antenna (LISA)

A Small Thank You to David Harding



LEFT: David Harding (left) and Stephen Toope (right) admire the gift of an original Compton Electrometer. This became the workhouse for precise electrical measurements for members of the Laboratory, many of whom are present in the famous 1932 photograph of the staff and research students in the Laboratory (below). There are nine past and future Nobel Prize winners in this photograph.



We were delighted that the Vice-Chancellor Stephen Toope was able to attend the Harding Symposium and to conclude the proceedings with a visionary speech about the huge potential of the coming generation of quantum sensors for science and society. The opportunity was taken to present David Harding with small gifts to mark his quite remarkable generosity in supporting the work of the University and, in particular, the Cavendish Laboratory.

The Compton Electrometer is a device for measuring voltage, or potential difference, very precisely. Invented by William Thomson (Lord Kelvin), the quadrant electrometer was significantly improved by the brothers Karl and Arthur Compton in the USA by increasing the charge on the needle of the torsion pendulum into the non-linear regime. Using negative feedback, the system was stabilized in an unstable regime. Arthur Compton worked for one year in the Cavendish Laboratory as one of the first

two US National Research Council fellows in 1919 before returning to the United States where he made his 1927 Nobel Prize winning discovery of the Compton effect. Compton electrometers were built commercially by the Cambridge Scientific Instrument Company. The instrument presented to David is one of six purchased by the Cavendish Laboratory. They were in constant use in teaching and research.



The electrometer and its presentation case.

Suchitra Sebastian recognised in the 2022 Breakthrough Prizes



We are delighted that **SUCHITRA SEBASTIAN** has been recognised by the Breakthrough Prize Foundation with the **2022 New Horizons Prize**, awarded to outstanding early-career researchers. She is one of four University of Cambridge researchers, along with Shankar Balasubramanian, David Klenerman and Jack Thorne, to receive a prize in recognition of their outstanding achievements.

Suchitra was awarded the Physics Prize for high precision electronic and magnetic measurements that have profoundly changed our understanding of high temperature superconductors and unconventional insulators. Her research seeks to discover exotic quantum phases of matter in complex materials. Her group's experiments involve tuning the co-operative behaviour of electrons within these materials by subjecting them to extreme conditions including low temperature, high applied pressure, and intense magnetic field. Under these conditions, they can take materials that are quite close to behaving like a superconductor – perfect, lossless conductors of electricity – and 'nudge' them, transforming their behaviour.

'I like to call it quantum alchemy – like turning soot into gold,' Suchitra said. 'You can start with a material that doesn't even conduct electricity, squeeze it under pressure, and discover that it transforms into a superconductor. Going forward, we may also discover new quantum phases of matter that we haven't even imagined.'

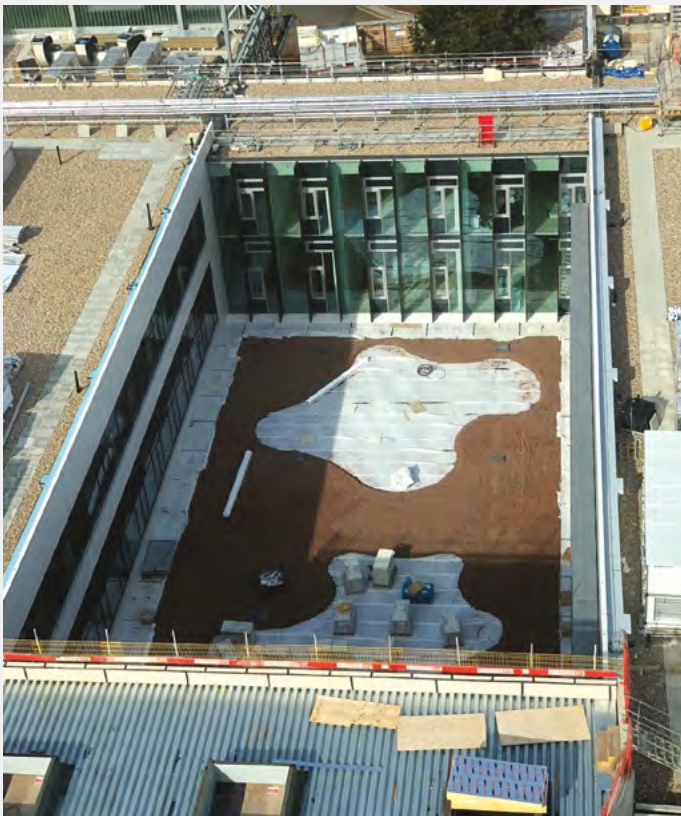
In addition to her physics research, Suchitra is also involved in theatre and the arts. She is Director of the Cavendish Arts-Science Project, which she founded in 2016. The programme has been conceived to question and explore material and immaterial universes through a dialogue between the arts and sciences.

'Being awarded the New Horizons Prize is incredibly encouraging, uplifting and joyous,' said Suchitra. 'It recognises a discovery made by our team of electrons doing what they're not supposed to do. It's gone from the moment of elation and disbelief at the discovery, and then trying to follow it through, when no one else quite thought it was possible or that it could be happening. It's been an incredible journey, and having it recognised in this way is incredibly rewarding.'

For the tenth year, the Breakthrough Prize recognises the world's top scientists. Each prize is US \$3 million and presented in the fields of Life Sciences, Fundamental Physics (one per year) and Mathematics (one per year). In addition, up to three New Horizons in Physics Prizes, up to three New Horizons in Mathematics Prizes and up to three Maryam Mirzakhani New Frontiers Prizes are given out to early-career researchers each year, each worth US \$100,000. The Breakthrough Prizes were founded by Sergey Brin, Priscilla Chan and Mark Zuckerberg, Yuri and Julia Milner, and Anne Wojcicki.

VANESSA BISMUTH, based on a news release which first appeared on the University of Cambridge website. Photography by Onur Pinar.

Ray Dolby Centre Progress



Construction of the Ray Dolby Centre has been progressively returning to the 'new normal' with works on site continuing to progress well. We are still maintaining restrictions on site to ensure the safety of the workforce but we are pleased to have been able to recommence the external department site visits, albeit with limited numbers.

Resources on site had, as usual, dropped over the Summer period although this year the impact has been noticeably greater with many workers returning home for the first time and taking extended breaks to visit their families. Our challenge ahead will be to ensure these resource levels increase in the face of a growing skills shortage across the construction industry in the UK and the ongoing issues with raw materials and products which have been impacted by many global events ranging from the pandemic and Brexit through to shortage of shipping containers, microchips and forest fires in Sweden!!

The structure of all the Wings is now substantially complete with the last sections of the complex steel structure in Wing 5,

the main entrance area, now complete. The final concrete slabs are being poured and the temporary scaffold towers around the precast columns being removed. This will allow the curtain wall façade to progress along the east elevation completing one of the most architecturally striking facades on the building.

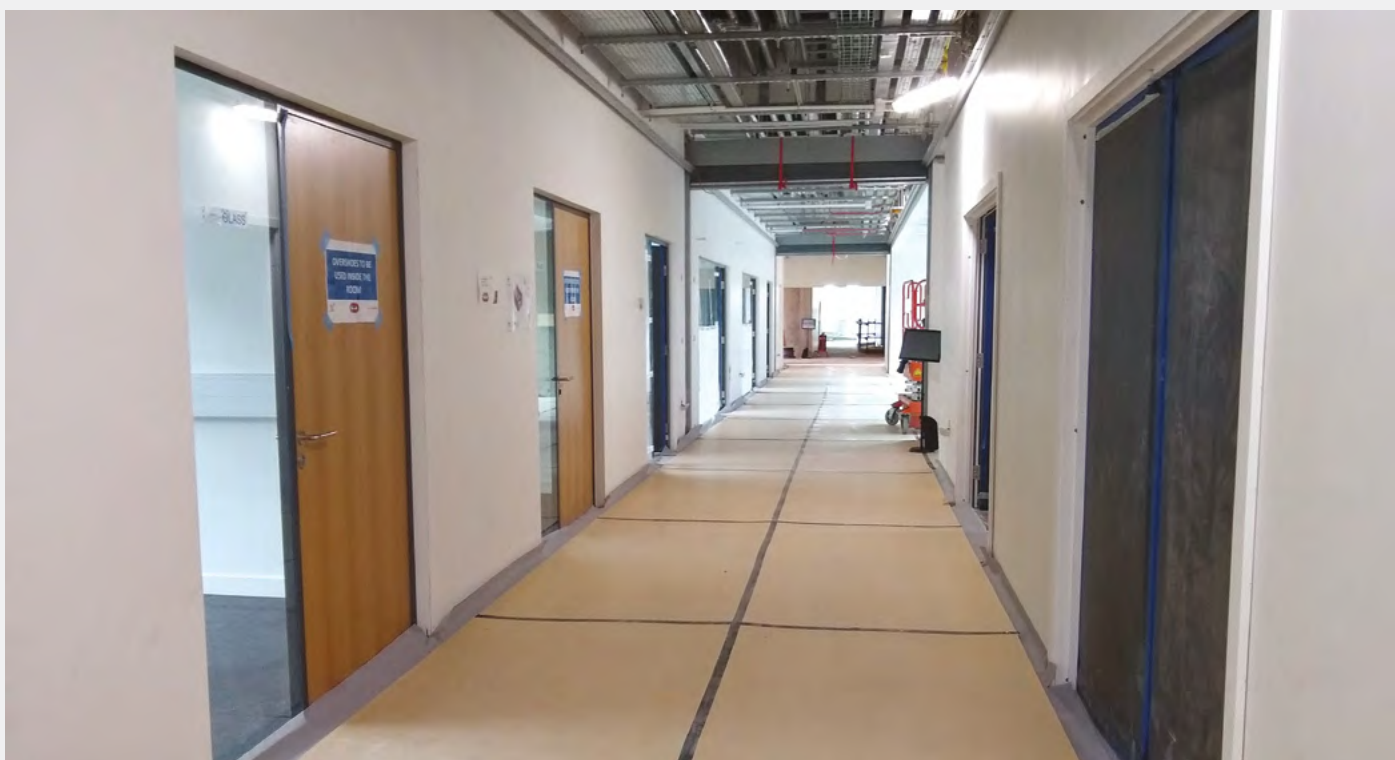
Unfortunately progress on the other areas of the building envelope has slowed over the last few months due to our façade subcontractor entering into liquidation. After a period of consolidation however, we have restarted the works and they are now progressing at a steady pace.

Internally the building continues to be transformed with the workshops and office spaces now progressing into the final fit out stage with joinery, decoration and floor finishes ongoing. The CUBs have also progressed over the last few months with mechanical and electrical plant being installed with the plan to commence energisation of the electrical supplies over the coming weeks which will allow the permanent lighting to be switched on progressively across the wings.

The Clean Rooms are also taking shape with the steel walkways installed in the service voids and the walk on ceiling grid now progressing. Next will be the raised access floor to the central cleanrooms followed by the ceiling grid installation

LEFT: The courtyard area of wing 5 to be used as a break-out area.
BELOW: Overview of the mechanical workshop in Wing 4, ground floor.





to the Deposition areas following inspection of the M & E services. These areas will now start to have reduced access to commence the first level of cleaning in preparation for the next phase of the works.

The Cryostat Halls have changed quite dramatically over the period with the timber partitioning now almost complete and the lifting gantries installed. M & E low level works will then progress to transform these areas into a finished condition. Another area which has progressed – although not visible to the external eye – are the internal courtyards where landscaping has now started. This gives a quite dramatic feel to the building and helps to give a good impression of how the final spaces will feel once occupied.

The Shared Facilities Hub is now approaching completion. The internal finishes have progressed well with the character of the building now really starting to take shape. This building will be an impressive addition to the West Campus offering a unique facility with a strong identity and a great space to study and socialise.

NEIL PIXSLEY



TOP: Office corridor in Wing 3 level 2.
BOTTOM: Cryostat timber partitions in Wing 1 level 0.

All photographs © Bougyues UK

Final year PhD student Stuart Macpherson wins Vice-Chancellor's Social Impact Award



Many congratulations to Cavendish PhD student **STUART MACPHERSON**, one of nine students to be recognised in this year's Vice Chancellor's Social Impact Awards.

Presented every year to students who show exceptional achievement and commitment to positive social change, the prize recognises Stuart's and his teammate Beth Tennyson's work on free, sustainability-themed teaching resources for primary schools.

Stuart's research focuses on understanding the physics of emerging solar photovoltaic technologies in Sam Strank's Laboratory. Stuart has co-developed the Primary School Energy Mapping Challenge aimed at 9–11 year olds. Through hands-on measurements and data logging, students increase their awareness about climate change and learn how to approach critically scientific problems and apply the knowledge gained to solve real-world problems. The project has already been piloted at 6 schools across the country.

In a blog for the Cambridge Hub, Stuart explains why he believes it is so important to engage with social and environmental causes whilst at university:

'Scientists have a responsibility to disseminate knowledge for the benefit of society. As a researcher of solar energy materials, I challenged myself to create forward-thinking, solutions-based projects to engage young people with issues surrounding climate, energy and sustainable living. The supportive environment of my research group provided me with an ideal space to develop approaches to connect with young people of all backgrounds in an inclusive manner, and to energise them on sustainability issues. I hope this award will help to stimulate further growth of these projects and I am deeply grateful for the recognition.'

Ongoing projects include 'The Primary School Energy Mapping Challenge' [1] which places children in the shoes of scientific researchers and tasks them with investigating the renewable energy potential of their school playground, promoting student



Students presenting their renewable energy plans for the island of Islay in the Inner Hebrides. The identities of the students are disguised with the 'Sustain/Education' charity logo for safeguarding reasons.

leadership and boosting scientific curiosity and confidence. Stuart, Beth and Sam are now setting up a new charity, 'Sustain/Education' [2] which will provide free multidisciplinary learning modules to augment the UK Year 5/6 school curriculum, offering activities which reinforce awareness of human relationships with energy and climate while supplying young people with tools and solutions to attack the problems facing our world. Stuart goes on:

'All students should be afforded the same space to explore new ideas and unleash their creativity. Whether working independently or with an organisation such as the Cambridge Hub, I would encourage all students to seek out this space and to use it to engage with social causes. Our collective efforts will make a huge difference.'

[1] <https://energymap.oe.phy.cam.ac.uk/>

[2] <https://sustaineducation.org/>

Watching the chemistry of a single proton in real time using atomically-trapped light



JEREMY BAUMBERG and BART DE NIJS (left) describe a new cascading nano-optics technique developed in the Cavendish Laboratory's NanoPhotonics Centre which allows efficient focussing of light down to a single atom, thus enabling researchers to observe individual molecules and their chemical changes.

Organic acids play crucial roles in the chemistry of life, catalytic processes, and the transformation of chemicals into useful materials. However, due to the dynamic nature of acids and the lack of sensitive-enough characterisation methods, in particular at material interfaces, it has remained unclear how such acids interact with their environment on a molecular level.

Now a new technique invented by the research team led by Jeremy Baumberg and Bart de Nijs at the Cavendish's NanoPhotonics Centre has shown that light can be efficiently trapped down to these fantastically-small scales. To this end a small refractive index lens is grown on a self-assembled gold nano-architecture resulting in unprecedented efficient atomic-scale focussing (Fig. 1). Combined with vibrational spectroscopy this now allows tiny molecules, otherwise too weak to detect, to be probed with single molecule sensitivity and in real-time. This enabled the researchers to study a small type of molecule consisting of only an organic acid group and a metal anchoring group (mercaptopropyl acid: MPA) eliminating any confounding factors. As a result, the

researchers were able to isolate and watch how a single acid group protonates, deprotonates, and complexes with metal surfaces in real time under various acidic conditions (Fig. 2).

In a paper published in *Science Advances*, the research team describes how, by watching such individual molecules for several minutes, they can reconstruct the energy landscape in which the ions sit, and uncover how such molecules experience their immediate environment. This new approach provides a direct means of observing the mysteries of the typically enigmatic catalytic processes at metal surfaces. These underpin many of today's chemical synthesis procedures used in the production of medicines, fertilisers, and has great potential in aiding the development of new catalysts and electronic IT devices based on molecules.

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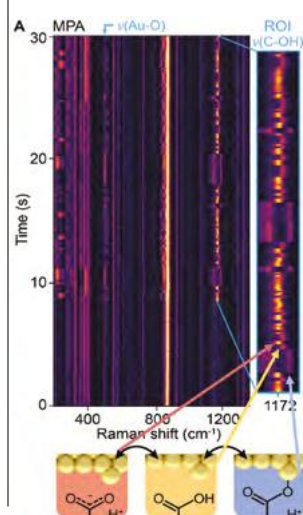
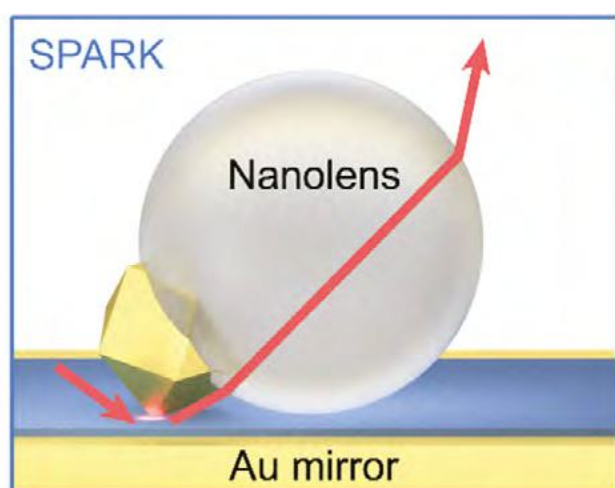


FIG 1 (left) Self-assembled Plasmonic nano-Architecture

Fig. 2 (right) Single-molecule chemical dynamics of MPA. (top) SPARK vibrational time series showing single-molecule dynamics of an organic group, with 50 ms integration time per spectrum. (bottom) Schematic diagrams of the three MPA picocavity states during the highlighted 30 second time window in the top image.

Cambridge researchers contribute to Human Capital Development in Africa: First Results from HERA



ELOY de LERA ACEDO describes the efforts made by him and his colleagues to enhance high-technology awareness and capability of young people in Africa. He also reports the first results of the HERA project which attempts to discover the elusive epoch of reionisation in the early Universe.

The 2021 African Radio Interferometry Winter School, a series of free online workshops presented by the South African Radio Astronomy Observatory (SARAO), in collaboration with Cambridge astronomers and the Radio Astronomy Techniques and Technology (RATT), took place virtually from 28th June to 2nd July.

The School focuses on theoretical and introductory tutorial aspects of radio interferometry to train the next generation of students and young professionals from South Africa and other African countries. Researchers from the Radio Experiment for the Analysis of Cosmic Hydrogen (REACH) project at Cavendish Astrophysics, the Kavli Institute for Cosmology in Cambridge and the Institute of Astronomy helped organize the school and delivered key lectures on radio cosmology, data analysis and instrument design.

REACH, a spin-off project from the Square Kilometre Array (SKA) project, is an international collaboration led by Cambridge, currently building a telescope in the remote semi-desert area of the Karoo in South Africa. REACH is partially funded by the Kavli Institute for Cosmology in Cambridge, Stellenbosch University and the Cambridge-Africa initiative.

The SKA project will be the largest radio telescope in the World at the time of its completion in 2028. The UK, and specifically a group of researchers at the Cavendish Laboratory, have led the design of many aspects of the telescope, such as software

for data analysis, array antennas, low noise electronics and electromagnetic modelling, for over a decade. The SKA telescope will tackle some of the most demanding projects in astronomy, including magnetic fields in the Universe, testing theories of gravity, understanding the origin of stars and life in the Universe.

As a vast international collaboration with hundreds of highly skilled people working on it, the SKA project offers many opportunities for making a wider impact in society, including human capital development in Africa. Radio Astronomy, thanks to the SKA, has gained prominence in the whole African continent, and specially in South Africa. There are many opportunities for the development of key skills for the next generations in engineering, science, mathematics, and many others. An impressive human capital development programme has been put in place, targeting the education and training of the next generation of African leaders in science and technology. The programme includes student bursaries, public events, workshops, schools and many others.



The 2020 school organized by the SARAO. Photographic Credit: SARAO.

REACH's involvement with these human capital development activities won't stop with the school, and the team is already preparing a 3-day Workshop focused on the science and technology behind REACH to take place in early 2022. This workshop, again part of the activities led by the SARAO, will allow a group of students to gain a deeper understanding and training on several STEM topics ranging from advanced mathematical modelling, statistics, electronics, digital systems and many more.

First Major Scientific Results from the Hydrogen Epoch of Re-ionization Array (HERA)

The formation of the first luminous celestial objects, and how they shaped the Cosmos, is one of the hottest topics in modern cosmology and astrophysics. It is also one of the hardest experiments to perform because of the extremely low amplitude of the cosmological signals, buried under foreground noise signals up to 100,000 brighter from the local Universe, our own Galaxy and terrestrial interference.

With the birth of the first stars from neutral hydrogen gas about 300 million years after the Big Bang, the whole Universe underwent a drastic transformation. The intergalactic medium (IGM) was heated and re-ionized by the energy emitted from the newly formed stars. Hence the name, the epoch-of-reionization. The gas clouds, which originally trapped the short-wave light from the first luminous objects, eventually became transparent to electromagnetic waves at all wavelengths, due to reionization, until eventually the neutral gas is concentrated in highly localized regions in the Universe.

Researchers have found a very clever way of studying this key milestone in the history of the Universe, not by observing the trapped direct light of the first stars, but by observing the re-radiation from the IGM hydrogen clouds. The hyperfine transition of neutral Hydrogen is emitted at a wavelength of 21-cm (1.42 GHz), but is observed on Earth at ~50-200 MHz because of the large redshifts at which the reionisation occurred. The radio signal contains key information about the energy emitted by the first stars.

Astronomers in the Cavendish Astrophysics group, the Kavli Institute for Cosmology in Cambridge and the Institute of Astronomy are participating in one of the main experiments attempting to detect this elusive radio signal. The experiment is called HERA, the Hydrogen Epoch of Re-ionisation Array, located in the semi desert area of the Karoo in South Africa. The project, led by Berkeley University in the US has partners across the US, UK, Europe and South Africa. Cambridge has been involved since the beginning of the project, leading the design of the front-end antennae and receiver systems. Currently we are analysing and interpreting the early data.

Only a few weeks ago, the project reported the first major scientific results in two journal papers.^{1,2} These results provide the best upper limits on the 21cm power spectrum by any interferometric experiment to date (Fig. 3). Even though the 21-cm power spectrum signal has not yet been detected, it is expected to be only about 2 orders of magnitude fainter than our best observations. The observations place a lower bound on X-ray heating, a previously unconstrained aspects of early galaxies. For example, if the CMB dominates the radio background at redshift $z \sim 8$, the new HERA limits imply that the first galaxies produced X-rays more efficiently than their local counterparts. The limits in the 21-cm signal reported by HERA also require even earlier heating if dark-matter interactions cool the hydrogen gas.

The HERA collaboration is now working towards the analysis of data from the new wideband system designed at the Cavendish, which not only upgrades the current system, but also increases its reach to beyond the Epoch-off-Reionization into the era often referred to as 'Cosmic Dawn'. The next Cavendish-led project is the REACH (Radio Experiment for the Analysis of Cosmic Hydrogen) telescope, which is aiming to make a definitive detection of the neutral hydrogen signal from the Epoch of Reionisation.

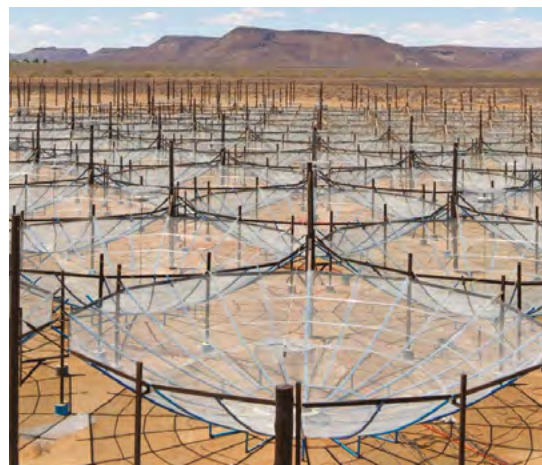


FIG 2: A view of the HERA telescope in the semi desert area of the Karoo.

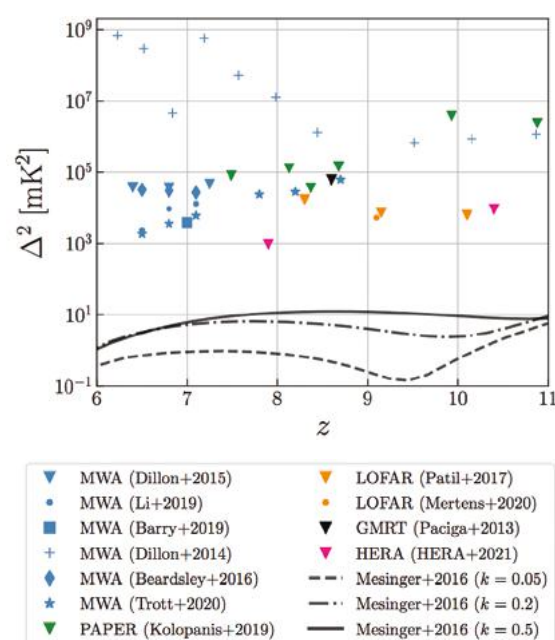


FIG. 3. The epoch of recombination power spectrum limits. The predictions of various models are shown by black lines. The new observations are shown by red inverted triangles.

1. First Results from HERA Phase I: Upper Limits on the Epoch of Reionization 21 cm Power Spectrum, The HERA Collaboration. arXiv e-prints: 2108.02263 August 2021.
2. HERA Phase I Limits on the Cosmic 21-cm Signal: Constraints on Astrophysics and Cosmology during the Epoch of Reionization. The HERA Collaboration. arXiv e-prints: 2108.07282, August 2021.

Poetry and motion: water molecules and ice nucleation



ANDY JARDINE and BILL ALLISON of the Surfaces, Microstructure and Fracture Group wax lyrical about their pioneering research on ice nucleation on graphene surfaces.

*'Waves trough – rebound –
and fury boil again,'*

is how John Clare described an overwhelming East-Anglian deluge in his 1830 poem, *'The flood'*. His romantic imagination was drawn irresistibly towards the unknown depths. Clare neither knew, nor probably cared, about the forces that underlie the motion of water.

Today, we care a lot because water and ice have such significance for the environment, as well as in technology; indeed, in every aspect of life. It is somewhat alarming to realise that, even now, much about the behaviour of water remains inexplicable or mysterious. Experimental measurements are difficult, and results are often contradictory, even more-so when one attempts to observe behaviour on an atomic scale. Technical difficulties arise because the hydrogen atoms in H_2O are all but invisible to electrons and synchrotron radiation, while OH and hydrogen bonds are easily dissociated by high-energy probes.

Our search for a low-energy, non-invasive probe with which to observe the motion of water molecules, led to a collaborative study recently published in *Nature Communications* [1]. The work involved experimentalists at the Cavendish Laboratory and Graz University of Technology, together with theorists from the University of Surrey. We used helium atoms, at extremely low energies, about 8 meV in our study, prior to ice formation on a pristine surface, where the motion of individual water monomers could be followed on atomic timescales.



FIG. 1. The Helium Spin-echo (HeSE) Microscope of the Cambridge Atom Scattering Centre. Photograph © Paul Raftery courtesy of Bougyues UK

The experiments were carried out in the recently established Cambridge Atom Scattering Centre [2] using the Helium Spin-echo (HeSE) method, now a general tool for exploring surface dynamics. It borrows ideas from neutron scattering to manipulate the nuclear spin of ^3He atoms and was developed to its present state-of-the-art at the Laboratory. It gives us the ability to isolate the behaviour of individual particles, as well as any cooperative effects that arise from the pairwise forces between molecules [3].

Fig. 2A illustrates the context of the measurements, showing a schematic trajectory for the motion of a water molecule on a graphene surface. Any motion on the surface induces a phase change in the scattered helium wave-packet, enabling the motion to be extracted by measuring the dephasing-rate of the surface correlation function (Fig. 2B). The variation of the

dephasing rate with scattering angle (strictly, the change in parallel wavevector, ΔK) allows us to identify the forces controlling the motion. The effect of forces can be seen from the simulated curves in Figure 1B, which shows the repulsive forces in red and the attractive forces in green. Comparison with the data, shown by blue markers, indicates that repulsive forces are at play and explains why the resulting energy barrier prevents the formation of ice islands on this graphitic surface. The observations overturn the conventional wisdom that short-range attraction is the most important process controlling ice formation.

Calculations show that water molecules at the surface have an enhanced dipole moment and the alignment of adjacent dipoles generates exactly the repulsive force seen in the experiment. Our results suggest new, broadly applicable, strategies for further suppressing, or otherwise controlling, ice formation by enhancing the dipole formed during adsorption. Such an effect could be achieved by, for example, using surface treatments leading to greater electron transfer, or in the case of graphene by altering the supporting substrate [4]. In these respects, the hydrophobic character of the graphene

substrate and particularly the adsorption geometry play important roles, but it seems reasonable to expect the dipolar effect could apply much more generally.

As techniques improve so does the sophistication of the analysis and the depths of insight go beyond what could ever have been foreseen. Research into water has itself become a flood and, as Clare might have it...

*'– On roars the flood – all restless
to be free
Like trouble wandering to eternity.'*

For more details of the instrument, see
www.nature.com/articles/s42254-021-00387-2

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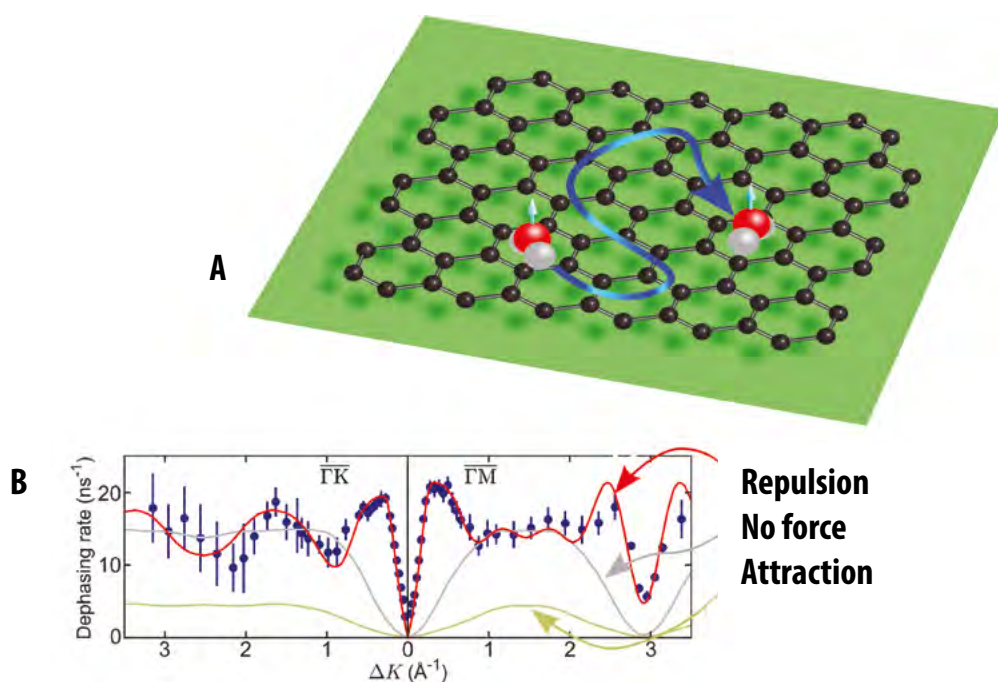


FIG 2, A: a water monomer moves freely on a graphene surface at 110K (blue trajectory). Measurements and calculations show that the preferred adsorption site is centred on the graphene hexagons. An energy barrier between adjacent sites results in a hopping motion involving neighbouring and next-neighbour sites. **B:** shows the angular dependence of scattering, allowing features of the motion to be deduced, such as its underlying periodicity and the intermolecular forces.

Room Temperature Coherent Exciton Condensates - A path to energy efficient ICT?



AKSHAY RAO and HOPE BRETSCHER describe recent research in which they and their colleagues have found evidence for an anomalous phase of matter that was predicted to exist in the 1960s. Harnessing its properties could pave the way to new technologies that would enable the sharing information without energy losses.

The information and communication technology (ICT) revolution of the past decades has transformed our way of life and opened up previously unimaginable opportunities for billions of people around the world. One of downsides of this has been the huge energy use of ICT, which is predicted to account for up to 20% of global electricity consumption by 2030. The fundamental challenge is that moving electrons around circuits requires energy. This energy is dissipated, lost as heat, during the functioning of the device. If we could find a way to move information around a circuit in a dissipationless manner it would be a paradigm shift for ICT. But this calls for completely new physical phenomena and materials to be investigated.

One intriguing possibility is the use of a class of materials known as Excitonic Insulators. Excitons are quasiparticles formed by the binding together of electrons and holes. In natural photosynthetic systems, the absorption of sunlight leads to the formation of excitons which then act as carriers of energy. They are funnelled extremely efficiently to the reaction centre where the excitons are converted to electrons and holes to drive redox chemistry. Thus, excitons

help power most of the bio-systems in the world. But they have many other exotic and as yet unexplored properties.

Beginning in the 1960s, theoretical physicists, including Neville Mott, then Cavendish Professor in the Laboratory, predicted the existence of a novel form of matter – the Excitonic Insulator. In such materials electrons and holes would spontaneously pair up to form excitons, without the need for external stimuli such as light. These excitons would then condense to form a macroscopic quantum coherent state, the excitonic insulator phase. This novel phase of matter might resemble Bose Einstein Condensates (BECs), which are observed in ultracold ensembles of gases. Perhaps most intriguingly, it has been suggested that the exciton insulator phase might persist up to room temperature!

Unfortunately, no clear experimental evidence for this state emerged over the last half century. Recently, however, hints have emerged that the layered material Ta_2NiSe_5 may show signs of an excitonic insulator state. We decided to investigate the material using a unique ultrafast optical microscope we have developed over



the past few years. This instrument allows us to track particles and quasi-particles in solid state systems with a spatial precision better than 10nm and a temporal resolution better and 10 fs. This is at the very limit of what is physically possible using optics and has opened a new window into quantum phenomena in a range of materials.

In Ta_2NiSe_5 we observed waves of energy rippling through the material when it was exposed to short and intense laser pulses. These oscillations, propagate outward from the zone excited by the laser in concentric circles, in the same way as dropping a rock into a pond disturbs the surface of the water and creates waves. Unexpectedly, these waves moved at a hundredth of the speed of light at room temperature, but disappeared when the material was heated above a certain 'critical temperature'.

Groups led by Andy Millis in New York, Philipp Werner in Fribourg and Nigel Cooper at the Cavendish, worked together to develop a theoretical model to explain the experimental observations. The results suggested that we were in fact observing the long sought for excitonic insulator phase of matter. The waves were a mode of this macroscopic

quantum coherent state coupling to the crystal structure in a completely new way and transmitting information across the condensate in a dissipationless manner. The theory also suggested that the excitonic insulator sits in between Bose-Einstein Condensates (BECs) and the BCS condensate of Cooper pairs that make superconductivity possible.

It is still early days for this class of materials and much work and many challenges lie ahead. Still, the observation that this state of matter can exist at room temperature and can perhaps transmit information in a dissipationless manner opens up fascinating possibilities of designing a new generation of ultra-low energy efficient circuits based on these quantum coherent exciton condensates.

ABOVE: Laser spectroscopy in Akshay's Laboratory in the Optoelectronics group (Photography by Akshay Rao).

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Developing the Outreach Programme

JACOB BUTLER describes new approaches to outreach in schools, designed to tackle underlying issues in the way we introduce science to young people

Alongside running outreach events, I have been studying for a *Transforming Practice* MEd at Cambridge. The course covers contemporary research in education and how its findings can be applied in practice. I intend to use this to enhance the work of the Outreach Office in the wider context of education, and to help shape the development of our programmes.

The course so far has consisted of three modules, each looking at a different area of education research and applying it in our activities. The first covered *Dialogue in Education*, looking at the work of the Cambridge Educational Dialogue Research (CEDiR) group¹ with members of its steering group. This research began in the 1980s, but the CEDiR group studies how it can be used as a pedagogical tool to aid teaching, working closely with teachers and education professionals. At school-level, Physics tends to be taught following a didactic, teacher-led approach - this module offered an interesting opportunity to present students with a novel way of engaging with the subject.

To test this, I ran a session with a group of Y11 students in the North of England using the CEDiR guidelines. The students set their own rules for respectful debate, discussed their ideas about topics covered in their Physics lessons, and then took part in a dialogue session introducing them to dimensional analysis, which they had not seen before. The feedback from students and their teacher was positive and suggested that a student-led discussion can be used to introduce new concepts as well as encouraging active engagement. The current Cambridge Physics Experience events include some elements intended to spark discussion in students, and this recent experience will be used to update and expand these.

The second module looked at *Learning without Limits*², a Cambridge project that addressed concerns about *ability-labelling* of students - the idea that students have a fixed level of academic ability that does not change over time. They developed a tool for evaluating and developing good educational practice, based on the experiences of teachers involved in the study, which aimed to be non-prescriptive and applicable to any educational context. The project had interesting parallels with the motivations behind our outreach programmes, namely, that students have the capacity to improve their educational outcomes, and that personal and environmental factors affect their ability to do so. Lockdown

meant that this module could not be applied practically, but a review of the literature showed a potential path for more widely sharing good practice in outreach.

Currently, this focuses on sharing of experiences and data gathered during events, which are interesting but rarely directly applicable in other outreach programmes. Following Learning without Limits' guideline format, a more general, place-agnostic approach may be possible, which allows common threads of good practice to be identified and practitioners to evaluate varied activities against a common metric.

The final module dealt with *place-responsive pedagogy*, an area of study that discusses the benefits of incorporating the place in which education occurs into the practice of educators. Part of the argument was that allowing students to immerse themselves in a variety of different environments benefits them in a multitude of ways, which ties nicely with the visits to Cambridge that form the backbone of our programmes.

A discussion on the concept of place and place-making, how people are both affected by and affect the areas in which they reside, highlighted an area for improvement in our events. Previously, we focused on the benefits of students visiting Cambridge, but neglected to show how Cambridge changes due to the people that attend it. Studies show that a feeling of 'not belonging' discourages many of the students we work with, and it is my hope that demonstrating how Cambridge is not a static institution, but one that grows and develops thanks to the people that make it, will help to address these concerns.

I will be developing our first programme aimed at Primary School students, hoping to lay the groundwork for a deeper understanding of Physics that will help to reverse the drop-off in enthusiasm for the subject that occurs during the first years of Secondary School.

1. www.educ.cam.ac.uk/research/groups/cedir
2. <https://learningwithoutlimits.educ.cam.ac.uk>

‘We had a good day ...!’ Outreach During Lockdown

STEPHEN MARTIN and JACOB BUTLER were delighted to receive the above message. It is just one comment from the schools who visited the virtual rendition of the Cambridge Physics Experience on-line in the last year!



A jar of water makes a fair enough converging lens, but is horribly astigmatic. So just use two! Then the problem arises that this is not a thin lens, so how can the students measure u and v ? No matter! Some sort of an estimate of its focal length can be made by finding one quarter of the minimum distance between an illuminated object and its focused image.

Over the last year, Outreach has moved entirely online. This has brought its own challenges but despite the upheaval we have engaged with over 1500 students and added a new element to our future activities. This blended approach offers a new means of engaging distant schools and will strengthen our future Outreach offerings.

The *Cambridge Physics Experience (CPE)* programme was converted into a series of virtual presentations each lasting about 20 minutes, which schools could use flexibly within their own local COVID constraints. This enabled us to present the whole programme to schools using our customary annual timetable, some of them using our materials over a period and others telling us that they had a virtual ‘day out’. We estimate that we reached a total number of students very similar to

the participation level in a normal year. In addition, a number of schools made new links with us, leading to ongoing collaborations in the coming year. Here is an example taken from our provision for Years 10 and 11. The practical element of our visits was vulnerable to school closure as it deprived students of access to lab apparatus: accordingly, lab experiments were re-cast so that they could be performed with common domestic items. For example, how can you do a lens experiment with no lens? (see caption above).

A personal element was added to the otherwise virtual package, by offering visitors a live Q&A session with either the Outreach officers or with the Isaac Physics team, to whom we are grateful for their particular input.

With ongoing uncertainties and the desire to keep the University’s staff and students safe, the Outreach department will continue to deliver our events online. This includes an entirely live, online version of Physics at Work, in which schools attend a series of talks by Physicists working in industry and academia to learn about the variety of careers open to those with qualifications in Physics. Exhibitors this year included several Cavendish research groups, industry scientists from TWI and MathWorks, and a nuclear-submarine engineer from the Royal Navy. The British Antarctic Survey’s Ozone Science Group also took part for their 31st consecutive year, making them our longest continuous contributor. We hope to be back to an in-person event next year, but this experience has shown an appetite for this event from more distant schools. To ensure we reach these schools, we will be looking at ways to stream the live event so that schools who cannot be there in person are at least able to attend virtually.

We acknowledge with thanks the support of the *Widening Participation Fund* and the *Institute of Physics* for making this work possible and express our gratitude to Lisa Jardine-Wright, Nicki Humphry-Baker and the Isaac Physics team for their ongoing input, help and encouragement, especially in relation to CPE.

JACOB BUTLER



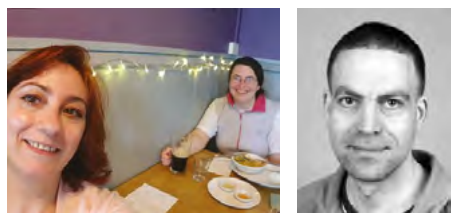
Physics. You work it out.

Update for the New Academic Year

INGRID MURRAY introduces several exciting new developments in the expanding Isaac Programme

New Content, Features and Team Members

The Isaac Physics Project continues to grow and evolve, with major developments in our Chemistry and Maths provision; support for younger students in Year 9; summer and consolidation programmes for GCSE and A Level students who may have missed out on learning due to the pandemic. We are also excited to announce our involvement with STEM SMART, a new free programme led by the University of Cambridge for disadvantaged students, launched in the news recently¹. STEM SMART is for students currently in year 12 and will follow them through to their A Level exams. Applications are open until 31st October. The programme is also currently recruiting paid university student and mature mentors for January - May 2022: to find out more and sign up please go to the online form at tinyurl.com/cusmartmentor



(left) Ingrid Murray, Teacher Support Manager on the left, and Andrea Chlebikova at a welcome dinner. (right) Rob Less

This summer, the Isaac Physics Project welcomed three interns to work with the team. The interns, who are STEM undergraduates at Cambridge, worked tirelessly to get our new GCSE Maths book and Year 9 Physics book ready for publication, with guidance from Senior Content Editor Lee Phillips and the authors, Sally and Jonathan Waugh, and Anton Machacek, Isaac's Associate Director. The interns gained valuable insight into the process of publication and we are grateful for all their hard work. Both of these books

will be available to purchase from January 2021. (<https://isaacbooks.org>)

Example - Calculate the voltage across the 50 Ω resistor.

Total resistance = $50\ \Omega + 70\ \Omega = 120\ \Omega$
 The 50 Ω resistor has a fraction $\frac{50\ \Omega}{120\ \Omega}$ of the total resistance.
 Its voltage = $\frac{50\ \Omega}{120\ \Omega} \times 12\ \text{V} = 5\ \text{V}$

23.1 A 25 Ω and a 75 Ω resistor are connected in series to a 6.0 V battery.
 (a) What is the voltage across the 25 Ω resistor?
 (b) What is the voltage across the 75 Ω resistor?

23.2 A 10 Ω, a 20 Ω and a 30 Ω resistor are all connected in series to a 24 V battery.

Isaac Physics also welcomed chemists Andrea Chlebikova and Rob Less to the team. They will be developing our Chemistry provision at GCSE and A Level.

The technical Isaac Physics team has also been developing new features alongside all our new content: new question types, tests, and an improved way of searching through our questions. Users can now search by subject and topic, and also educational function: whether the user is looking to practise a particular concept or challenge themselves²:

Our pre-made tests are designed for teachers to assess their students' understanding in particular areas of the curriculum from year 10 through to year 13³. They can choose whether the students receive feedback immediately or once everyone has completed the test and also the level of feedback given. These tests will be developed further over the coming months.



Summer Teacher and Student Events

In July 2021, over 100 teachers joined the Isaac Physics team online for a three-day Teacher Symposium, aimed at

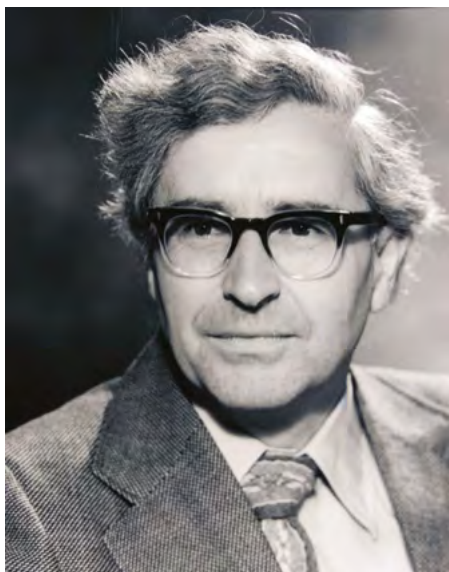
introducing the host of new features on the site, including our Summer Support Programme; networking; and trialling material from the new books. Teachers commented:

'It was good to get a better idea for what is available from Isaac Physics and how the resources can be used. It was also good to see previews of what was coming up in the future.'

We also held our first Awards Ceremony for Expert Teachers and Embedded Schools, a recognition system for teachers and schools who are using and promoting Isaac Physics consistently throughout the academic year. Award holders received a certificate, a logo to use on their school website or personal email, and resources to support their use of Isaac Physics. A total of 59 teachers and headteachers attended the online event. Other online events run in the summer were the long running Senior Physics Challenge for highly active students on Isaac Physics, the Sutton Trust Physics Summer School, and the Year 12 August Bootcamp. Both events are to support students from backgrounds with low progression to higher education. On the Bootcamp, the Isaac staff delivered small group tutorials, augmented by our Isaac Ambassadors, who are practising school teachers and have a wealth of experience in using and promoting Isaac Physics. Our ambassador team will be heading new Isaac Physics regional hubs to support schools in embedding Isaac Physics in their teaching. They will also be participating in our new free Teacher CPD (Continuous Professional Development) courses.

To find out more about the Isaac Physics, our events and resources for students and teachers, please visit <https://isaacphysics.org>.

1. www.cam.ac.uk/stemsmart
2. <https://isaacphysics.org/gameboards/new>
3. <https://isaacphysics.org/quizzes>



Antony Hewish (1924–2021)

We are very sad to report the death of Antony (Tony) Hewish on 13 September 2021 at the age of 97. He will be remembered as the pioneer radio astronomer who led the team of researchers who identified the first pulsar at the Cavendish's Mullard Radio Astronomy Observatory.

Tony came up to Cambridge in 1942 to read natural sciences. After his second year, however, he was sent for war service at the Telecommunications Research Establishment (TRE), Malvern where Martin Ryle was head of the radar counter-measures group. Tony worked on devices to jam the radar systems of hostile night-fighters.

Tony completed his physics degree on returning to Cambridge in 1946 and then joined the newly-founded radio astronomy group led by Martin. Tony was the group's expert in the phenomenon of radio scintillation, the twinkling of radio sources caused by plasma irregularities along the line of sight to the source. In 1951-52, he worked out in detail the theory of radio source scintillation and in 1964 the phenomenon was observed in compact radio sources. These sources included the recently discovered quasars, among the



Tony Hewish with the 4.5 acre scintillation array at the Lord's Bridge Observatory

most extreme examples of active galactic nuclei.

Tony designed a large, low-frequency array to address a number of issues raised by these observations: the discovery of more quasars by observing the scintillation of the radio sources, the determination of their angular sizes and the measurement of the structure and properties of the solar wind. With a DSIR grant of £17,286, he and his team constructed a 4.5-acre array to detect radio source scintillation at low frequencies. Jocelyn Bell (-Burnell) joined the project as a graduate student in October 1965. She was fully involved in the construction of the array, becoming responsible for the network of cables connecting the dipoles, helping commission the array and analysing the data.

Jocelyn had the demanding task of analysing the large amount of data arriving each day by hand. On 6 August 1967, she discovered a strange strongly scintillating source in a region of sky where the scintillations were expected to be small. The source disappeared but then reappeared in November. Observations made with higher signal-to-noise ratio on 28 November 1967 showed that these were not scintillations but a train of very stable pulses with pulse period 1.33 seconds.

Tony described the following two months as the most exciting of his scientific career.

Nothing like this had been observed in astronomy before and the team had to be absolutely certain of the correctness of the observations. It was essential to ensure that all sources of terrestrial inference could be excluded. If the source were associated with extraterrestrial emissions, including the notorious 'Little Green Men (LGM)'; the motion of a planet about the parent star would be easily detectable - no orbital motion was observed. The low frequency signals displayed dispersion, enabling a rough distance of 65 pc to be estimated. In continuing her analysis of the unrelenting flood of data, Jocelyn discovered three other pulsars including one with a period of only 0.25 seconds. The discovery was kept under tight wraps until Tony and his colleagues were absolutely convinced that they had discovered a new astronomical phenomenon, what became known as the pulsars.

The pulsars were soon identified with magnetised, rotating neutron stars, one of the key discoveries of modern astronomy. Their discovery had implications for understanding all types of explosive events in astronomy, including the violent events occurring in active galaxies. The pulsar array was no longer the appropriate instrument for further pulsar discoveries and so Tony used the scintillation technique to study 'interplanetary weather', in particular to



The pulsar model built in the radio astronomy workshop.

identify major plasma outbursts from the Sun which could impact the GPS system.

Tony and Martin were awarded the 1974 Nobel Prize in Physics 'For their pioneering research in radio astrophysics: Ryle for his observations and inventions, in particular of the aperture synthesis technique, and Hewish for his decisive role in the discovery of pulsars.' Some have argued that, because of her role in the discovery of pulsars, Jocelyn should have shared the Nobel prize.

Tony was head of the Mullard Radio Astronomy Observatory from 1982-88. His research achievements were firmly based on the long Cavendish tradition of using ingenuity and imagination to construct innovative low-cost instruments with a small team of dedicated research students and assistant staff working within an exhilarating research environment.

We pass on to Tony's family our sincere condolences, but remember fondly his friendly support and appreciate his deep understanding of physics.

MALCOLM LONGAIR

Richard J. Eden OBE (1922–2021)

Members of the Laboratory will be sad to learn of the death of Richard Eden at the age of 99. He received his Cambridge doctorate in 1951 under the supervision of Paul Dirac. He won the distinguished Smith's Prize in 1949 and was elected to a Fellowship at Clare College in 1951. His areas of research at that time were in quantum field theory, nuclear physics and high energy physics. He was a pioneer of the S-matrix theory of particle physics and with Peter Landshoff, Keith Olive and John Polkinghorne wrote the definitive account of the theory in their book, *The Analytic S-Matrix* (1966).

When the Department of Applied Mathematics and Theoretical Physics was founded in 1959, many of the theorists who were housed in the Cavendish, chose to join the new Department, but Richard preferred to remain in the Cavendish where he created a theoretical group within the High Energy Physics group.

The energy crisis of the early 1970s led him to analyse in detail various newspaper claims about the nature of the problem and he soon changed the focus of this research from particle physics to energy studies. In 1974 he founded the Energy Research Group in the Laboratory and from 1982 was Professor of Energy Studies until his retirement in 1989. From 1974, he served on the UK Advisory Committee for Energy Conservation. In many ways, he was far ahead of his time in recognising the need for serious research in energy studies and his



Part of Conversation Piece by Bob Tulloch, 1984. Courtesy of Clare Hall.

group was a considerable success in training PhD students in the necessary tools to make the discipline the subject of serious analytic academic study.

Richard played a major role in the founding of Clare Hall in 1966. He drew up the plans for the College and persuaded Clare College of the importance of this initiative. The project was a very significant success, playing a key role in welcoming distinguished visitors to Cambridge from all over the world and particularly in somewhat more remote disciplines from those needed for college teaching purposes. He was Vice-President of the College and published a book on the College's history in 2009.

We pass on to his family our sincere condolences on this sad event.

MALCOLM LONGAIR



Richard with members of the Energy Research Group.

Jocelyn Bell Burnell wins the Royal Society Copley Medal



Jocelyn Bell Burnell is only the second woman to be awarded the world's oldest scientific prize, the Royal Society's Copley Medal, for her role in the discovery of pulsars in the Laboratory in 1967. This is the Society's most prestigious award.

Oleg Brandt awarded a UKRI Future Leaders Fellowship to lead innovation using cosmic ray detectors



Many congratulations to **Oleg Brandt**, who has been awarded a £1.5 million Future Leaders Fellowship by UK Research and Innovation (UKRI) to accelerate his research and lead innovation using cosmic ray detectors (see CavMag25).

Royal Society University Research Fellowships 2021



Many congratulations to **Bart De Nijs**, **Alice Thorneywork** and **Dorian Gangloff** (left to right) who are among the 37 successful Royal Society University Research Fellows candidates for 2021.

Royal Society University Research Fellowships 2020



Deepak Venkateshvaran was awarded a 2020 Royal Society URF, joining the Laboratory in January 2021. We pass on many belated congratulations. He designs and develops exploratory nanoscale devices for biochemical sensing, materials characterisation and for the study of fundamental physical phenomena in the Optoelectronics Group.

Leverhulme Trust Fellowship success for early career researchers



Congratulations to **René Poncelet** (left) and **Jan Behrends** (right) who have been awarded the prestigious Leverhulme Trust Early Career Fellowships.

Cavendish Student awarded grant from innovative Institute of Physics Research-scholarships fund



Cavendish student **Ayngaran Thavanesan** has been awarded one of this year's prestigious grants from the Bell Burnell Graduate Scholarship Fund. Ayngaran will be completing his PhD in theoretical cosmology at the Kavli Institute for Cosmology under the supervision of Will Handley.

Simone Eizagirre Barker has been awarded the D.J. Lovell Scholarship by the SPIE



Simone Eizagirre works in the EPSRC Doctoral Training Centre in Nanoscience and Nanotechnology, supervised by **Mete Atatüre** and **Sam Stranks**.

New Stephen Hawking fellow



We are delighted to welcome back **Sophie Renner** having been awarded the Stephen Hawking Fellowship by UK Research and Innovation (UKRI).

Volker Heine Young Investigator Award



Congratulations to **Bingqing Cheng** from the TCM group, winner of the Psi-k Volker Heine Young Investigators Award for outstanding computational work in the areas covered by the European Research Network Psi-k mission.

IOP Bates Prize 2021



Many congratulations to **Rohit Chikkaraddy** (NanoPhotonics), who has won the 2021 IOP Bates Prize as an outstanding early career researcher in quantum, atomic, molecular and plasma physics.

IEEE Stuart R. Wenham Young Professional Award for Dr Sam Stranks



Congratulations to **Sam Stranks** on winning the IEEE Stuart R. Wenham Young Professional Award at the 48th IEEE Photovoltaic Specialists Conference. The Award recognizes individuals who have made significant contributions to the science and technology of photovoltaic energy conversion, including work on photovoltaic materials, devices, modules, and/or systems.

2021 EPS High Energy and Particle Physics prize awarded to Bryan Webber and Torbjörn Sjöstrand



Many congratulations to Professor Emeritus of Theoretical Physics **Bryan Webber** for being awarded, together with **Torbjörn Sjöstrand**, the 2021 EPS High Energy and Particle Physics prize. The Prize, established in 1989, is awarded every two years for an outstanding contribution to high energy and particle physics.

We welcome **Rituparno Chowdhury** (Kapitza/OE) as a new Marie Curie Fellow.

OPPOSITE A collage of images of the rapid development of the construction of the Ray Dolby Centre. All photographs © Bougyues UK.

New Appointments

We are very pleased to welcome the following administrative and support staff members to the Laboratory.

Helen Llewelyn (NanoDTC) Nano DTC Administrator

Louise Hilton (HR) HR Administrator (Maternity cover)

Zoe Gardner (Finance) Project Purchasing Coordinator

Andrew Colledge (Rutherford Hub) General Administrator

Luciana Carvalho Faissal (Accounts) Project Finance Administrator (Secondment)

Andrea Chlebikova (Isaac Physics) Senior Project Chemist

Robert Less (Isaac Physics) Senior Project Chemist

Scott Dell (Workshop) Senior Workshop Technician

Robbie Yuan (Finance Team) Deputy Finance Manager

Lata Sahonta is the new Programme Manager for the Department's Winton Programme for the Physics of Sustainability, as well as the Research Manager for the Energy Transitions interdisciplinary research centre, both based at the Maxwell Centre



STEMSMART
An Initiative from the University of Cambridge



Are you studying **maths** with **physics**, **chemistry** or **further maths**?

Are you considering applying for a **physical science** or **engineering** course at university?

STEM SMART is a **FREE** programme for Y12 students from state schools, beginning in January 2022 and supporting students through to May 2023.

STEM SMART includes weekly online tutorials with Cambridge University subject specialists, access to student mentors and lectures from top scientists. The programme will support and extend your school learning.

To find out more, check your eligibility and apply, go to www.cam.ac.uk/stemsmart

Apply by 31st October 2021





How you can contribute

Online Giving

The University's Office for Development and Alumni Relations (CUDAR) has made it easier to make donations online to the Department and to two of our special programmes. If you wish to make a donation to the Department, please go to:

campaign.cam.ac.uk/giving/physics

If you wish to support the graduate student programme, please go to: **campaign.cam.ac.uk/giving/physics/graduate-support**

If you wish to support our outreach activities, please go to: **campaign.cam.ac.uk/giving/physics/outreach**

If you would like your gift to be applied to some other specific aspect of the Development Programme, please contact Andy Parker or Malcolm Longair. The Development portfolio is described in CavMag 18 and can be viewed online at: **www.phy.cam.ac.uk/alumni/files/Cavmag18Aug2017online.pdf**

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A Gift in Your Will

One very effective way of contributing to the long-term development of the Laboratory's programme is through the provision of a legacy in one's will. This has the beneficial effect that legacies are exempt from tax and so reduce liability for inheritance tax. The University provides advice about how legacies can be written into one's will. Go to: **campaign.cam.ac.uk/how-to-give** and at the bottom of the page there is a pdf file entitled **A Gift in Your Will**.

It is important that, if you wish to support the Cavendish, or some specific aspect of our development programme, your intentions should be spelled out explicitly in your will. We can suggest suitable forms of words to match your intentions. Please contact either Malcolm Longair (**msl1000@cam.ac.uk**) or Samantha Stokes (**departmental.administrator@phy.cam.ac.uk**) who can provide confidential advice.

If you would like to discuss how you might contribute to the Cavendish's Development Programme, please contact either Malcolm Longair (**msl1000@cam.ac.uk**) or Andy Parker (**hod@phy.cam.ac.uk**), who will be very pleased to talk to you confidentially.