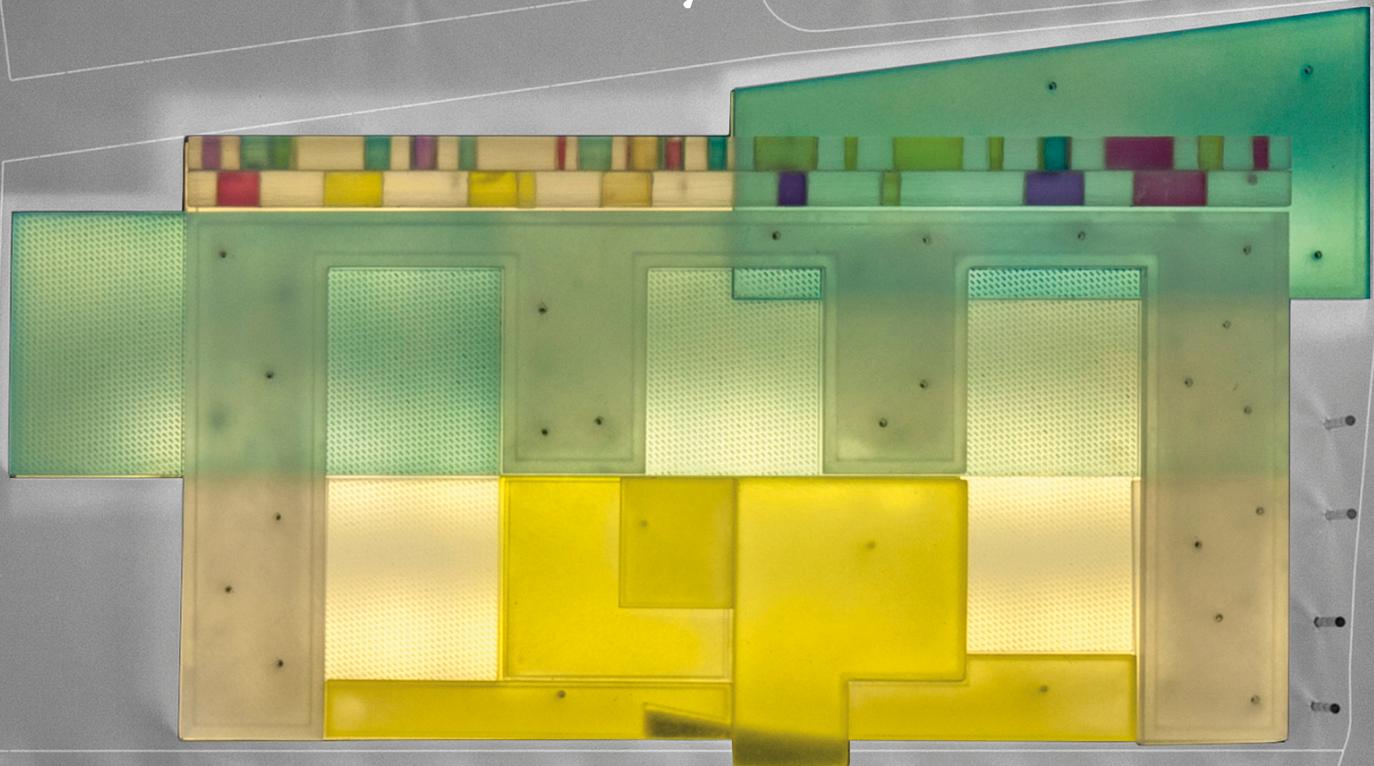




# CAVMAG

News from the Cavendish Laboratory

£75 million Government  
investment in the  
Cavendish Laboratory



MADINGLY ROAD

JJ THOMSON AVENUE

The Physics of  
Swimming

Deep Underground  
Neutrinos

Atmospheric  
Variability on an  
Alien World

**What a couple of months it has been! The funding of the Cavendish III project to the tune of £75 million by government, matched by £75 million from the University, is an enormous step forward in the rebuilding of the Laboratory. Jestico and Whiles have been appointed project architects. The Maxwell Centre has been handed over to the Laboratory and the opening will take place in April. These are exciting times.**

**But we have to continue our development efforts to complete the Cavendish III project and we have an ongoing need to seek support and development funds for the long term.**

**Your support for all these initiatives is greatly appreciated.**

Malcolm Longair

**INSIDE**

|   |    |
|---|----|
| Cavendish III   | 2  |
| Maxwell Centre  | 3  |
| G.I. Taylor and the Physics of Swimming                           | 4  |
| DUNE, the Deep Underground Neutrino Experiment, goes global       | 6  |
| Many-body Quantum Dynamics in Optical lattices: More is different | 8  |
| The serendipitous discovery of variability in an alien world      | 10 |
| Optofluidics group in NanoPhotonics                               | 12 |
| The AMI Telescope Upgrade   | 14 |
| The Isaac Physics Project: A close run thing                      | 16 |
| Physics at Work 2015  | 17 |
| Uncovering Maxwell  | 18 |
| Winton Symposium 2015   | 20 |
| Cavendish Graduate Conference 2015                                | 22 |
| John Shakeshaft, Radio Astronomer 1929–2015                       | 23 |
| Who was A.W. Scott?   | 24 |
| Cavendish News  | 26 |
| How You Can Contribute  | 28 |

**In the Chancellor of the Exchequer’s Autumn Statement, the Government announced a £75 million investment in the Cavendish Laboratory. This will be matched by a further £75 million from the University to make a huge contribution towards the redevelopment of the Laboratory.**

**T**he Vice-Chancellor, Sir Leszek Borysiewicz, said: “This is fantastic news. The Cavendish is and will serve as a national asset, to the benefit of research both in Cambridge and across the UK.

**“ This announcement demonstrates the Government’s commitment to regional and national scientific growth and innovation. It presents a major opportunity for us to create a world-leading facility in the heart of the greater Cambridge high-tech cluster and deliver a step-change in physical science research capability in the UK. ”**

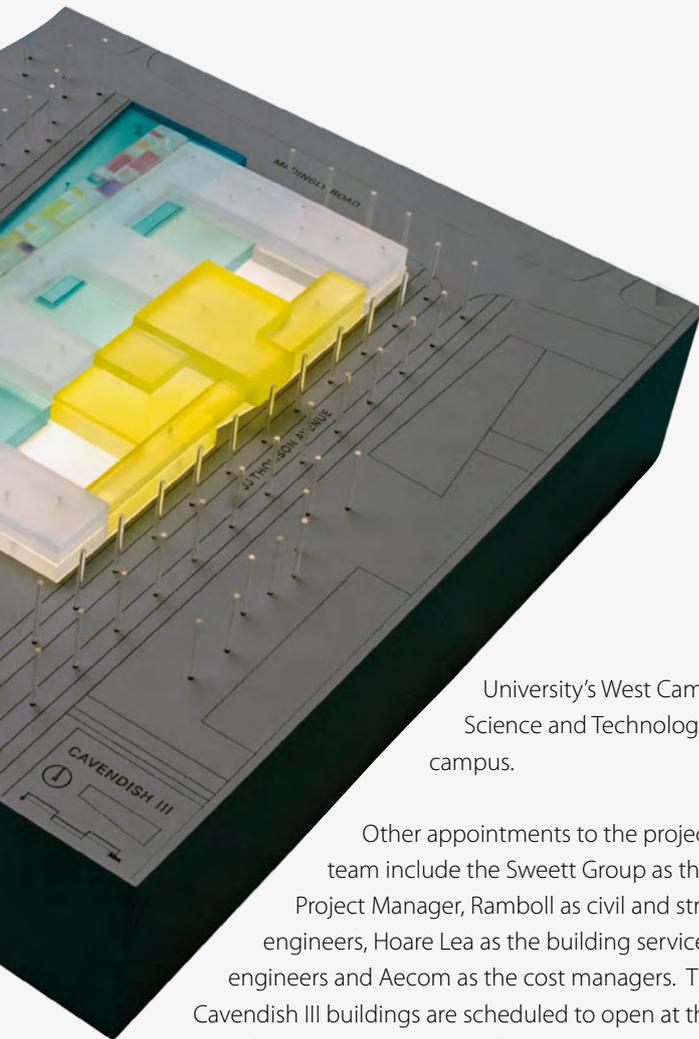
Andy Parker, Head of the Physics Department, said “Thanks to this welcome announcement we look forward to working with partners in Government and industry and other universities to further the globally important research which this department undertakes.

“The Cavendish Laboratory has an extraordinary history of discovery and innovation in physics since its opening in 1874. This funding allows us to continue the tradition of innovation and originality that has been at the heart of the laboratory’s programme since its foundation.”

Almost at the same time, it was announced that the award-winning architects Jestico + Whiles, with CH2M as laboratory specialists, have won the contest to design the new Cavendish Laboratory building, what we call the Cavendish III project. This major new project to replace the existing Cavendish buildings is planned to be constructed on the



**Cover image:** Architect’s model showing the Cavendish III building, viewed from above. Courtesy of Jestico and Whiles.



University's West Cambridge Science and Technology campus.

Other appointments to the project team include the Sweett Group as the Project Manager, Ramboll as civil and structural engineers, Hoare Lea as the building services engineers and Aecom as the cost managers. The Cavendish III buildings are scheduled to open at the end of 2020, with construction expected to start in 2018.

The Cavendish III building will house a number of Physics research groups, their laboratories, office and support accommodation, along with reception, teaching, library, outreach, exhibition, common room and other functions. The building will meet stringent vibration criteria, electromagnetic interference and other technical requirements.

Tony Ling, Director at Jestico + Whiles said: "We are thrilled to be working on this world-leading laboratory. Our proposals for the new facility will support the ground-breaking research into Physics and cognate sciences that has been taking place at Cambridge for over 140 years and will contribute to the University's wider development for West Cambridge."

**IMAGE, ABOVE:** Architect's model showing the Cavendish III building, on the West Cambridge site. Courtesy of Jestico and Whiles.



## Opening for Business

On 23 November 2015, the Maxwell Centre was formally handed over to the Cavendish Laboratory and since that date research groups are beginning to move their activities into the new Centre. The formal opening will take place in April 2016, by which time a number of activities will have completed their moves into the Centre.

The Centre will act as a focus for industrial engagement with the physical sciences on the University's Science and Technology campus in West Cambridge. Very soon, the Maxwell Centre web-site will come into operation where many more details of the activities can be found. In addition, the web-site will describe how companies and other organisations can become partners in the Maxwell Centre. The site address will be: [www.maxwell.cam.ac.uk](http://www.maxwell.cam.ac.uk).

In the meantime, if you want more information, please contact Dr. Agnieszka (Aga) Iwasiewicz-Wabnig at [aga@maxwell.cam.ac.uk](mailto:aga@maxwell.cam.ac.uk).



**IMAGE, ABOVE:** The entrance to the Maxwell Centre from the South, looking along J.J. Thomson Avenue. © Kelvin Fagan

# G.I. Taylor and the Physics of Swimming



**Do sperm swim like fish? This question was first addressed by Geoffrey Ingham (G.I.) Taylor (1886 – 1975). OTTI CROZE and FRANÇOIS PEAUDECERF describe his pioneering studies of the physics of swimming and their present relevance to biophysics research and the sustainability agenda.**

**G**.I. Taylor's passion was for the mechanics of fluids - his essay on the structure of shock waves won him a Smith's prize in 1910 and at the age of only 25, he became Reader in Dynamical Meteorology at Cambridge. Taylor loved the sea and ships and became the meteorologist on the *Scotia* expedition, aimed at understanding iceberg formation following the sinking of the Titanic. He used kites and balloons in new ways to measure accurately the vertical distributions of temperature, humidity and wind velocity in the atmosphere. This fieldwork inspired his life-long interest in turbulence, a field to which he contributed several breakthroughs. For example, realizing that turbulent diffusion is a continuous process, in contrast to molecular diffusion, Taylor developed a new statistical description of turbulent transport. After working in aeronautics during WWI, Taylor returned to Cambridge as lecturer in Mathematics. There he became good friends with Cavendish Professor Ernest Rutherford, who allocated him laboratory space next to his own in the Cavendish Laboratory.

Taylor had a knack for doing both theory *and* experiments to the highest standard. His innovations were often inspired by practical problems. For example, he used his understanding of mechanical stability to design a more efficient type of anchor, the CQR (secure) plough anchor, now commonly used in small boats.

After WW2, he began his studies of the physics of swimming microorganisms, inspired by Victor Rothschild's observations



FIG. 1.

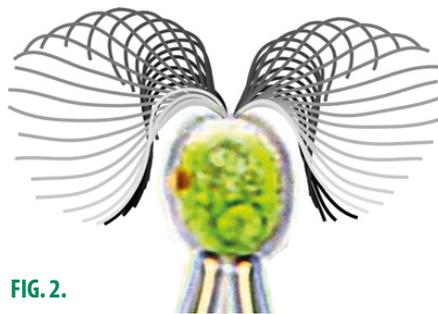


FIG. 2.

of sperm swimming. Taylor addressed the intriguing question - do sperm swim like fish? Taylor realized that these organisms, one microscopic and one macroscopic, pose quite distinct problems in fluid physics. The relative importance of inertial and viscous forces on a swimmer is quantified by the Reynolds number:  $Re = UL\rho/\mu$  with  $U$  and  $L$  the typical swimmer, or flow, speed and size, and  $\rho$  and  $\mu$  the fluid density and viscosity, respectively. For large  $Re$ , inertia dominates over viscosity. Fish living in a high Reynolds number environment,  $Re > 10^3$ , are propelled by exploiting inertia, pushing fluid back by shedding vortices and drifting forward. Sperm and other swimming microorganisms live in a low  $Re$  ( $\sim 10^{-4}$ ) world dominated by viscosity. For them water is like treacle and inertia of no use. Low  $Re$  flows are time-reversible: symmetric swimming strokes get you nowhere - imagine stirring syrup

up and down. To make progress, swimming microbes have evolved symmetry-breaking propulsion. For example, bacteria spin helical flagella, sperm wave them, as originally studied by Taylor, and the bi-flagellate algae we work with beat them to perform a microscopic breaststroke (Figure 2).

Taylor created some wonderful demonstrations that put into stark contrast the differences between the physics employed by swimmers at different  $Re$ . A robot fish (Figure 3), like children's bathtime toys, swims by beating its tail to and fro. Placed in water, the fish swims well; in treacle, where its  $Re$  is the same as for microbes, it goes nowhere. Robot bacteria, however, happily swim in treacle by rotating helical wire flagellae (Figure 3). A box was recently found in the Cavendish Laboratory containing Taylor's robot swimmers. Inspired by this, we asked Colin Hitch and David Page-Croft at the G. K. Batchelor Laboratory in the Department of Applied Mathematics and Theoretical Physics (DAMTP) to make replicas of the bacteria and fish robots. These now work well and will be wonderful for teaching and outreach events.

The physics of life at low Reynolds number pioneered by Taylor underlies much current research. This includes our own work on the statistical and fluid mechanics of suspensions of swimmers biased by environmental cues, such as chemicals, gravity or flow. Bacteria, too short to detect gradients along their body, swim in an alternation of straight runs and random reorientations. This swimming pattern and a short-term memory allow bacteria to probe their chemical environment, climbing up nutrient gradients (chemotaxis). Our research



**FIG. 3.**

is concerned with chemotaxis in porous media like soil, and its role in the symbiotic dynamics of algae and bacteria depending on each other for nutrients. The swimming and reorientations of chemotactic bacteria are described by the low Re mechanics Taylor discovered. The latter also describes the reorientation of bottom-heavy swimming algae, predicted from low Re ('torque-free') balances between gravitational and viscous torques acting on these swimmers. This helps understand suspensions of swimming algae in flows, with application to

industrial photobioreactors (see box). Taylor's scientific legacy underpins practically all of modern fluid dynamics and much of what we now call soft matter and biological physics. It is also the basis of many engineering and industrial processes. Taylor's legacy also lives on in the research programme of DAMTP, theoretically and in a dedicated fluids laboratory. Taylor's modern day replicas can continue to inspire and keep alive the memory of his exceptional contributions.

**FIG. 1.** G. I. Taylor with his wife Stephanie sailing away from the Norwegian Lofoten Islands in 1927.

**FIG. 2.** (a) The asymmetric swimming flagellar beat of the alga *Chlamydomonas*, held here on a micropipette (Image courtesy of K. Wan).

**FIG. 3.** Taylor's mechanical robot swimmers: fish flap their tails and bacteria spin helical flagella, both models powered by twisted rubber bands. The wind-up duck flaps its feet. These models were recently rediscovered in the Cavendish Laboratory.

Videos of the model fish and sperm are now available at: [www.damtp.cam.ac.uk/user/gold/movies.html](http://www.damtp.cam.ac.uk/user/gold/movies.html)

**FURTHER READING**

- G. Batchelor, *The Life and Legacy of G. I. Taylor*, CUP (1996)
- G. I. Taylor, Analysis of the swimming of microscopic organisms. *Proc. R. Soc. Lond. Ser. A* **209** 447 (1951)
- M. D. Haw & O. A. Croze Physics comes to life, *Physics World* **25** (2012)

**Otti Croze writes:** My group studies the physics of microorganisms in biotechnological and ecological contexts. Our research focuses on the physics of microswimmers, photobioreactors and symbiosis. Photobioreactors are devices for growing algae for valuable bioproducts and bioenergy. Algal suspensions invariably flow through transparent pipes or channels, but current designs do not account for the peculiar physics of algae swimming in a flow. Theory predicts swimmer self-concentration in down-welling flows and non-canonical dispersion, which we derived by extending Taylor's dispersion theory to swimmers [1]. We are using photobioreactors to test these predictions, in collaboration with co-workers at DAMTP and Plant Sciences. Di Jin has set up an 'air-lift' photobioreactor that quantifies swimmer and fluid dynamics. She is using it to compare stochastic computer simulations and experiments and will soon explore the effects of light-bias, phototaxis, and the coupling of swimming and growth. Our symbiosis research includes the study of 'distant symbiosis': algae need vitamins to make sugars and bacteria, requiring sugars to make vitamins interact through a diffusive bridge, passing only the necessary metabolites and not cells. A mathematical model I developed with François Peaudecerf predicts survival conditions for these partner populations. Experimental tests are in progress. This work, in collaboration with Alison Smith's group in Plant Sciences, is relevant to microbial communities where mutualistic partners are spatially separated, for example, in microbial mats. Part III projects will also soon consider the effects of swimming on algal-bacterial symbiosis. We are also developing methods to detect metabolites. For example, Hannah Laeverenz Schlogelhofer has been using genetically modified algae responsive to vitamin B<sub>12</sub>. Ongoing research on microswimmer physics has involved understanding the strange trajectory ordering of the alga *Dunaliella salina* in oscillatory flows [2], and measuring helical swimming parameters of algae using the new technique of Differential Dynamic Microscopy [1].

[1] M. A. Bees & O. A. Croze *Biofuels* **5**, 53 (2014) <http://dx.doi.org/10.4155/bfs.13.66>

[2] A. Hope, O. A. Croze, W. C. K. Poon, M. A. Bees & M. D. Haw, *Preprint* arXiv:1507.07176

**Figure above:** Bioconvection patterns formed by *Dunaliella salina*, a swimming, beta-carotene producing alga. The alga is bottom-heavy and so gravity makes it swim up. In a flow, an additional viscous torque causes swimming toward down-welling fluid. The pattern results from an interplay of fluid dynamics and swimming. Similar physics are relevant in photobioreactors to grow algae.

# DUNE, the Deep Underground Neutrino Experiment, goes global



**MARK THOMSON**, co-spokesperson of the DUNE collaboration, describes this major international neutrino experiment in which almost 800 scientists and engineers from 145 institutes in 26 nations are taking part.

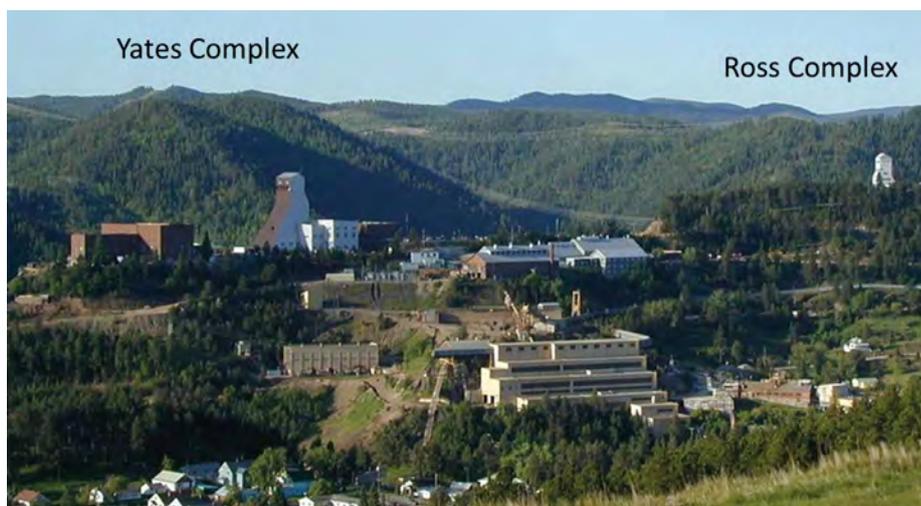
## Neutrinos – a Nobel Story

**T**here are more neutrinos in the universe than any other type of matter particle. There are more than 300 neutrinos in every cubic centimetre of the universe and every second over  $10^{15}$

neutrinos pass through each and everyone of us. From an experimental perspective, that's the problem – neutrinos interact with matter only through the weak interaction, which, as its name suggests, means that neutrinos freely pass through matter and only very rarely interact with it. Twenty years ago very little was known about neutrinos, except that they were believed to be massless and came in three types or 'flavours' ( $\nu_e$ ,  $\nu_\mu$ ,  $\nu_\tau$ ), the electron, muon and tau neutrinos. The flavours simply labelled the types of particles they produced when they underwent a rare interaction. For example, an electron neutrino ( $\nu_e$ ) would produce an electron. Even then, however, there were hints that neutrinos weren't behaving quite as expected. The rate of detection of electron neutrinos from the Sun was less than half that expected, a result for which Ray Davis Jr. received the Nobel Prize in Physics in 2002. This deficit prompted a major programme of research into neutrino physics, which culminated in the award of the 2015 Nobel Prize in Physics to Takaaki Kajita and Art McDonald 'for the discovery of neutrino oscillations, which shows that neutrinos have mass.'

## Neutrino Oscillations

Kajita led the Super-Kamiokande experiment in Japan, which in 1998 provided conclusive



**FIG. 1.** The above-ground facilities at the Homestake mine in South Dakota. This is where Ray David made his discovery of the deficit of solar electron neutrinos.

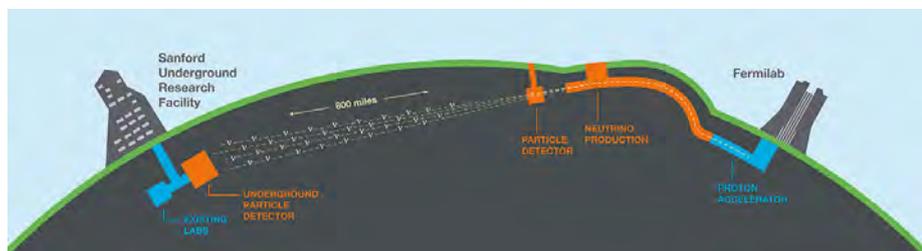
evidence that neutrinos produced in the atmosphere were changing their identities as they travelled through the Earth on their way to the 50,000 ton Super-Kamiokande detector. About half the muon neutrinos appeared to be changing into another type of neutrino when they travelled over a distance of about 1000 km. The Sudbury Neutrino Experiment (SNO) led by McDonald, demonstrated conclusively that the electron neutrinos from the Sun weren't simply 'disappearing' but were changing their identities into muon and tau neutrinos. Taken together, the results of the Super-Kamiokande and SNO experiments provided clear evidence for the phenomenon of neutrino oscillations. Neutrino oscillations are a quantum mechanical process whereby the observed 'flavour eigenstates', for example the electron neutrino, are not in fact fundamental particles, but coherent quantum mechanical linear superpositions of the three fundamental neutrino states, now known

as  $\nu_1$ ,  $\nu_2$  and  $\nu_3$ . This leads to transitions, or oscillations, between different states as neutrinos propagate over very long distances, for example,  $\nu_e \leftrightarrow \nu_\mu$ . Along with the discovery of the Higgs boson at the Large Hadron Collider (LHC), the discovery of and study of neutrino oscillations represents the biggest step forward in particle physics of the last two decades. One of the consequences of neutrino oscillations is that we now know that neutrinos have mass, although the masses are very much smaller than those of the other fundamental matter particles.

## The Next Big Thing – the Deep Underground Neutrino Experiment (DUNE)

The Deep Underground Neutrino Experiment (DUNE) is a billion-dollar scale next-generation neutrino oscillation experiment, currently

**FIG. 2.** The Deep Underground Neutrino Experiment will search for CP violation in the neutrino sector using a 1,300 kilometre-long beam from Fermilab to the Sanford Underground Research Facility.



under review by the U.S. Department of Energy (DOE). DUNE has an ambitious and potentially game-changing scientific programme for neutrino physics and for astroparticle physics. The DUNE collaboration currently consists of almost 800 scientists and engineers from 145 institutes in 26 nations, indicative of the global interest in the innovative science made possible with the DUNE near and far detectors and the proposed Long Baseline Neutrino Facility (LBNF) at the Fermilab. LBNF/DUNE consists of a new powerful (1.2 MW) neutrino beam at the Fermi National Accelerator Laboratory (Fermilab), which is located about 40 miles from downtown Chicago. The neutrino beam is fired 1300 km through the Earth's crust to the proposed 70,000 ton DUNE far detector at the Homestake mine in Lead, South Dakota (Fig. 1). The aim is to start construction of DUNE in 2017 with first operation of the neutrino beam in 2025.

### The DUNE Far and Near Detectors

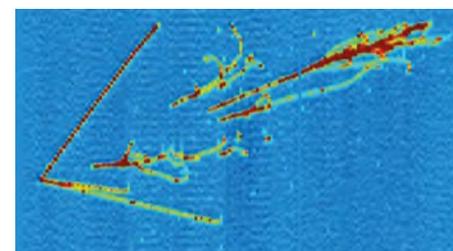
The neutrino beam will be directed towards a near and a far detector (Fig. 2). DUNE's far detector will be located 1.5 km underground at the Sanford Underground Research Facility (SURF) in South Dakota. After travelling 1300 km through the Earth's crust, the neutrino flavour oscillations will be observed. This DUNE far detector will consist of four 17,000 ton Liquid Argon Time Projection Chambers (LAR-TPCs). Each of the four detectors will consist of a vast 62 m x 15 m x 14 m cryostat filled with ultra-pure liquid argon at 87.3 K. Any charged particle in the argon volume, produced by a neutrino interaction or some other mechanism, will ionize the argon. The liberated

ionization electrons drift in a strong electric field (500 V/cm) towards the walls of read-out wire planes, which are 12 m high and span the entire length of the detector. By detecting this charge as a function of time it is possible to image in three dimensions any charged particle track in this enormous detector (Fig. 3). This advanced detection technology has been used before, but never on this scale. The DUNE near detector on the Fermilab site will observe the un-oscillated neutrino beam providing constraints on experimental uncertainties. By the standards of neutrino physics, the near detector event rates are incredible – it will detect hundreds of millions of neutrino interactions. This will enable a diverse and world-leading neutrino physics programme in addition to the study of neutrino oscillations.

### DUNE Science – Targeting CP Violation

Early in the Universe matter and antimatter particles were created in equal amounts. All things being equal, one would expect the matter and antimatter to annihilate subsequently leaving a Universe filled with light, but essentially no matter. This is clearly not what happened - some matter was left over and this has formed the galaxies that populate the Universe. For this to happen there must be some small but fundamental difference between the way matter and antimatter behave – this is known as charge-parity (CP) symmetry violation. CP violation has been observed for hadrons, the particles made from quarks, but this cannot explain the observed matter-antimatter asymmetry in the Universe. Our current best bet is known as leptogenesis, requiring CP violation in the

**FIG. 3.** An example of a neutrino interaction in a small Liquid Argon Time Projection Chamber (LAR-TPC).



neutrino sector. However CP violation has not been observed for neutrinos – to observe this subtle effect requires an intense beam and a vast detector, namely LBNF/DUNE. By studying neutrino oscillations first with neutrinos and then with antineutrinos, the antimatter particles of neutrinos, DUNE aims to discover CP violation in the neutrino sector and to measure the corresponding CP phase angle,  $\delta$ . Because of the very long baseline, DUNE will also conclusively determine the neutrino mass ordering, normal versus inverted hierarchy, and provide a sensitive test of our current understanding of neutrino physics, the so-called three-flavour paradigm – there may yet be further surprises lurking in the neutrino sector.

### DUNE Science – Beyond Neutrino Oscillations

DUNE is not only about neutrinos. The large far detector with photograph-like imaging capability located deep underground provides an opportunity to search for proton decay. Proton decay has never been observed, but is expected in almost all models of physics that provide a unified picture of all forces. It is known that the lifetime of the proton is greater than  $10^{33}$  years. There are approximately  $10^{34}$  protons in the argon in the DUNE far detector and the exquisite imaging power of the LAR-TPC detector technology means that a single proton decay can be observed and identified with minimal background. DUNE is particularly well suited to search for proton decay modes with kaons in the final state (such as  $p \rightarrow K^+ + \text{antineutrino}$ ), which are favoured in many super-symmetric (SUSY) extensions to the



**FIG. 4.** Some of the almost 800 members of the DUNE collaboration. Mark Thomson is in the blue shirt in the very centre of the front row.

Standard Model of particle physics.

A core-collapse supernova is an intense source of neutrinos – it radiates most of its energy in neutrinos, not light. DUNE will provide unique capabilities for the observation of neutrinos from Type-II core-collapse supernovae that occur anywhere in our Galaxy. Unlike water Cherenkov detectors, which are primarily sensitive to electron antineutrinos from supernova neutrino bursts, DUNE is mostly sensitive to the electron neutrinos. This would enable DUNE to observe directly the initial stage of formation of a neutron star ( $p + e^- \rightarrow n + \nu_e$ ) in 'real time', albeit delayed by several years – this would be a truly remarkable observation! There is even the possibility of observing the formation of a black hole as a sharp cut-off in the time spectrum of the SNB neutrinos, if the black hole were to form a few seconds after the stellar core collapse.

#### **DUNE: from Concept to Reality**

In the last year, progress with DUNE has been very rapid; LBNF/DUNE produced a four-volume conceptual design report (CDR) in July 2015, detailing the design of the DUNE near and far detectors and the design of LBNF, which encompasses both the new neutrino beam line at Fermilab and civil

facilities for the DUNE detectors. Assuming that funding is secured, excavation will commence in 2017 and installation of the first far detector module is planned to start in 2021. In parallel DUNE is undertaking an extensive detector prototyping programme at CERN. ProtoDUNE, the large-scale engineering prototype for the DUNE far detector was approved by CERN in September 2015 and construction will start in 2016.

LBNF/DUNE is a billion-dollar scale project. It will be the largest particle physics project ever undertaken in the USA and will be the flagship of the U.S. particle physics programme, just as the LHC is the flagship for European particle physics. Scientists from many nations are playing key roles (Fig. 4) with a very strong interest from UK physicists, supported by the STFC. There is still a long way to go, but the signs are good; in the next few years we believe we will have launched the next major project in particle physics to continue the exploration of the physics of the elusive neutrino.

#### **FURTHER READING:**

<http://lbnf.fnal.gov> and [www.dunescience.org](http://www.dunescience.org)

## Many-body Quantum Dynamics in Optical lattices: More is different



We are delighted to welcome **ULRICH SCHNEIDER** as a new Lecturer in the Atomic, Mesoscopic and Optical Physics

**Group. Prior to taking up this post, he was a Senior Scientist/Group Leader within the Quantum Optics group at the Ludwig-Maximilians Universität in Munich.**

One of the fundamental boundaries of knowledge in modern Physics is Quantum Complexity. Despite our thorough understanding of the relevant microscopic physics —electromagnetism and quantum statistics — we do not necessarily understand the resulting many-body physics in complex materials such as high-temperature superconductors and topological materials or during photosynthesis. As commented by Nobel laureate and past-Professor of Theoretical Physics in the Laboratory, Phil Anderson: 'More is Different'. We are interested in genuine many-body phenomena, meaning emergent phenomena that only occur when many particles come together, typical examples being superfluidity and magnetism.

The microscopic world is rich in fascinating effects where emergent collective phenomena give rise to a behaviour that is totally different from that of its individual constituents. While a single electron would never display ferromagnetic or superfluid

properties, the electrons in a solid piece of material such as a crystal can, collectively, do just that.

However, experiments in these areas typically face significant challenges as both the length and the time scales they probe are extremely small. Therefore, we study experimentally this type of physics in an enlarged artificial model system. Instead of electrons we use complete atoms, several thousand times heavier and therefore slower, while the role of the periodic crystal potential is played by an optical potential, a so-called optical lattice (see Fig. 1). These differences result in the characteristic time scale, the hopping time from one lattice site to the next, being of the order of milliseconds instead of femtoseconds. This allows us to manipulate and observe the system's evolution in real-time, thereby enabling studies of its non-equilibrium dynamics, which is typically a much richer problem than that of the equilibrium states.

We effectively build a quantum simulator for condensed matter physics, where we can study many-body phenomena in a very clean and precisely controlled system and have all the tools of quantum optics at our disposal. This field received a lot of attention once it was demonstrated that strongly correlated systems could also be realised in this way, starting with bosonic Mott insulators in 2002 and later extended to fermionic particles by us and others in 2008.

These unique possibilities, however, come at a significant cost. Since the particles are much heavier and the densities are much lower, all energy scales are massively reduced and we need nanokelvin temperatures to study the physics of room temperature electrons. Therefore, we are employing ultracold atoms, that is, Bose-Einstein condensates and degenerate Fermi gases that have been cooled to the required temperatures by laser and evaporative cooling, drawing heavily on quantum optics techniques.

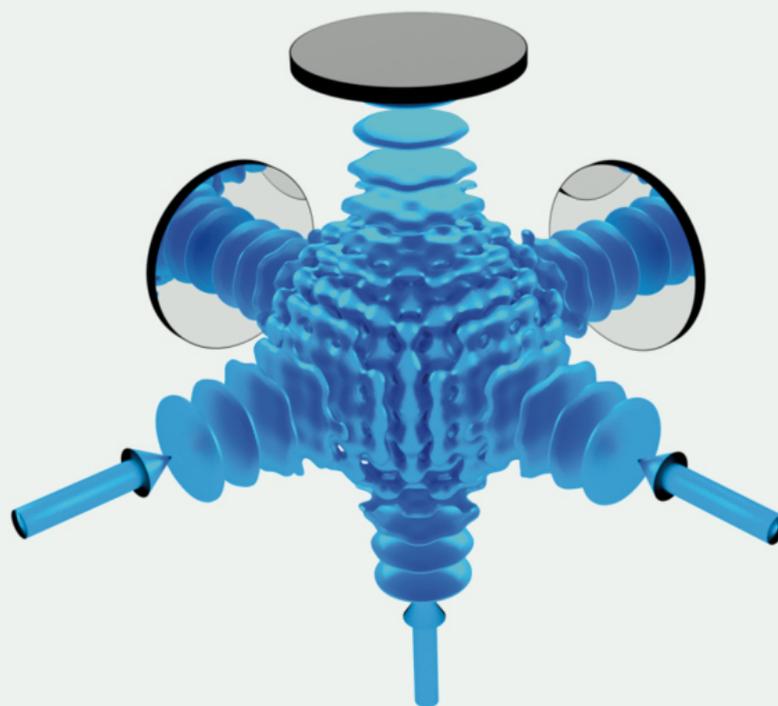
The resulting systems are extremely well isolated from any thermal environment—

the atoms are at the centre of an ultra-high vacuum chamber and are held in place solely by magnetic and optical fields. They therefore need to find their own internal, self-consistent thermal equilibrium. This creates a novel scenario—an isolated system, that differs from typical solid-state experiments, where the environment ultimately dictates the final temperature at which the system thermalises. One striking example of novel effects has been our achievement of negative absolute temperatures. We experimentally demonstrated the existence of stable equilibrium states in which most particles accumulate near their maximum energy states, that is the upper band edge, requiring the system to be described by a negative absolute temperature. This was the first time that this well-established — but maybe not so well-known — concept could be applied to mobile particles. Before, it had only been considered in the context of localised (nuclear) spins.

In addition, this toolbox enables us to synthesise genuinely new many-body systems and investigate novel effects. During the

last year, we exploited the isolated nature of the system to study a totally new many-body phenomenon dubbed Many-Body Localization. This describes a system of interacting particles in the presence of external disorder whose dynamics is non-ergodic, that is, that will never thermalise, and therefore lies outside traditional statistical mechanics. Contrary to thermalising systems, which 'forget' their initial states except for their initial energy, many-body localised systems will retain quasi-local memory of their initial quantum states for long times. They not only require new methods to describe them, but potentially enable quantum information devices with vastly increased coherence times.

We are currently building a novel setup that will extend our capabilities to shape optical potentials to include non-periodic potentials such as Optical Quasicrystals related to the celebrated Penrose tiling. These potentials promise to host novel many-body physics with even more unusual properties.



**FIG. 1.** An optical lattice is an optical standing wave created by overlapping three laser beams (arrows) that are retro-reflected by three individual mirrors (shown schematically). The resulting lattice constant is of the order of the optical wavelength (500-1000nm), compared with Angstroms in real solids.

# The serendipitous discovery of variability in an alien world



**BRICE-OLIVIER DEMORY, NIKKU MADHUSUDHAN and DIDIER QUELOZ report the detection of wildly changing temperatures on a super Earth – the first time any atmospheric variability has been observed on a rocky planet outside the solar system.**

**M**ore than two thousand years ago, Epicurus wrote to Herodotus about the plurality of worlds:

**‘There are an infinite number of worlds, some like this world, others unlike it.’**

Just twenty years ago, the seminal discovery of the first planet orbiting another star outside our Solar System echoed Epicurus’ words. The discovery of the first exoplanet brought a whole new field of astronomy and astrophysics to life. Today, a few thousands of these alien worlds have been found with a wide range of masses, sizes, temperatures, and orbital architectures. The statistics are building up to help answer the historical question: ‘how many planets are out there?’. We know today that almost every star like our Sun is likely to host an orbiting planet and about one in every six stars hosts an Earth-size planet. Scorched surfaces, icy interiors, disintegrating planets and puffy gas giants represent an incredible diversity in the exoplanet population. One can genuinely wonder whether the solar system is the norm, or the exception.

The most common class of exoplanets consists of the so-called super-Earths with masses between 1-10 times that of the Earth. Surprisingly, no such planet exists in our solar system, but they are the lowest-mass exoplanets whose atmospheres are observable with current and upcoming instrumentation.

Thirty light years from our home planet lies 55 Cancri e, a super Earth that is 90% larger than the Earth and eight times more massive. Remarkably, a ‘year’ on 55 Cancri e lasts only 18 hours. Because of its proximity to the host star, this planet is properly roasted with temperatures in excess of 2000 degrees.

In 2011, our team discovered that 55 Cancri e was transiting in front of its host star, producing periodic eclipses as seen from the Earth. This fortunate geometry allowed us to measure the size of the planet during transit and its temperature when the planet is occulted by its host star half an orbit later. 55 Cancri e’s host star is visible to the naked eye and thus provides huge numbers of photons for astronomers to play with. Because of this, 55 Cancri e is often referred to as a Rosetta stone for our understanding of hot super-Earth exoplanets. Knowing that its mass is eight times the Earth’s and its radius originally thought to be 2.17 Earth radii, a result first published in 2011, suggested that 55 Cancri e was neither rocky nor gaseous but contained a rocky core surrounded by a large envelope of water, which would have contributed 20% of the total planetary mass – a true water-world. This water would have had to have been in a super-critical state and there were no clear clues from the theory of its interior about how this picture could be correct under the extremely intense irradiation from the host star.

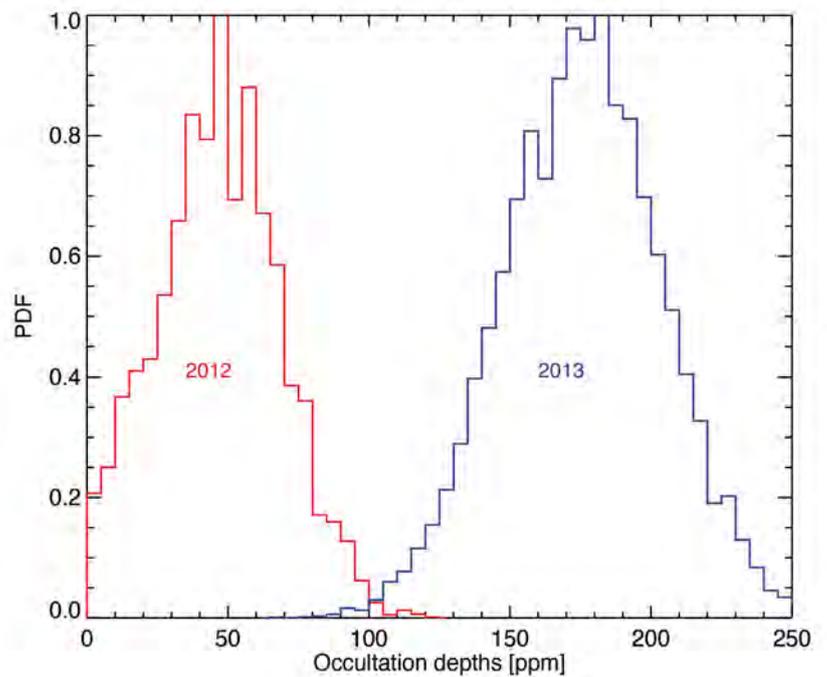
Between 2012 and 2013, NASA awarded us more than 100 hours of observing time with the Spitzer Space Telescope to obtain

a dozen transits and occultations of 55 Cancri e. The Spitzer telescope operates in the near-infrared, 3 to 5 micron waveband, where the planetary spectral energy density peaks. Each occultation thus represents an opportunity to measure 55 Cancri e’s brightness temperature from the dip in flux density due to the planet disappearing behind its star. An important first result from the analysis of this large dataset was that the planet was smaller than thought, 1.92 Earth radii, resulting in a 45% increase in density compared to our 2011 data and the possibility that the planet could be rocky, surrounded by a thin atmosphere.

Looking for minute signals in noisy data motivates astronomers to stack the data together in order to extract shallow transits and occultations. Then, the overall signal-to-noise ratio is increased, but any potential change in the planetary properties with time is averaged out. At first, we did not even look at the individual datasets, but stacked them directly for the purpose of the analysis. It was only one year later, when we reanalysed the whole dataset with novel techniques, that we decided to look at each dataset independently. To our surprise, the planet was varying with time.

Most dramatically, the data from 2012 showed no clear signal from the planet. At that time, 55 Cancri e’s thermal emission was very weak with a measured brightness temperature of less than 1500 degrees. One year later, in 2013, the signal was very strong with measured temperatures reaching 3000 degrees. Fig. 1 illustrates this variation in the planet’s infrared emission as measured by

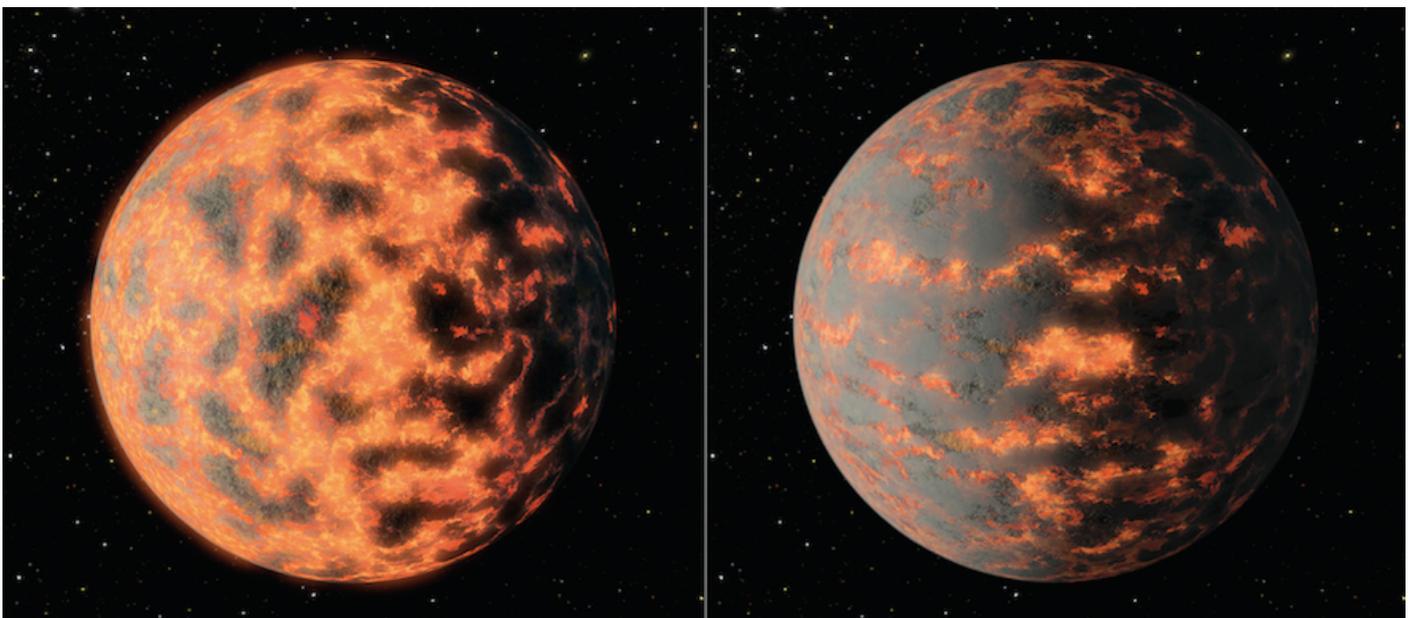
Spitzer between 2012 (red) and 2013 (blue). A possible explanation could be that large-scale volcanism is taking place on the surface of 55 Cancri e and that the plumes spewed out from volcanoes blanket the planet's thermal emission which originates from the underlying layers. In this picture, volcanic activity would have been high in 2012 and low in 2013. It is unclear however if the ejected material could survive long enough at these high temperatures to be observable. Silicates would rapidly sublime and could not form plumes with significant opacity to match our observations. Alternately, volatile materials in 55 Cancri e could have been distilled from its rocks and only aluminium and calcium oxides would remain, surviving the harsh temperatures. If our interpretation based on volcanism is correct, 2012 would qualify as an active year with significant amounts of aerosols lofted up in the atmosphere, while 2013 would be rated a quiet year with mostly clear skies. An artist's depiction of what 55 Cancri e might look like is shown in Figure 2.



**FIG. 1. (ABOVE)** 55 Cancri e's average occultation depths in 2012 (red) and 2013 (blue). The posterior probability distribution functions are shown for each year, illustrating the difference in occultation depths measured with the Spitzer Space Telescope.

The analysis of this extensive campaign started with the same preconceived notion promoted by Aristotle two millennia ago: the immutability of the world beyond the Moon. The present study reminds us, that no matter however new the field of exoplanet research, after two millennia we are still subject to the old demon.

**FIG.2. (BELOW)** Artist's impression of 55 Cancri e based on our observations. The left panel illustrates the planet in a quiescent state, while the right panel represents the planet during an active volcanic phase with very little seen from the surface.



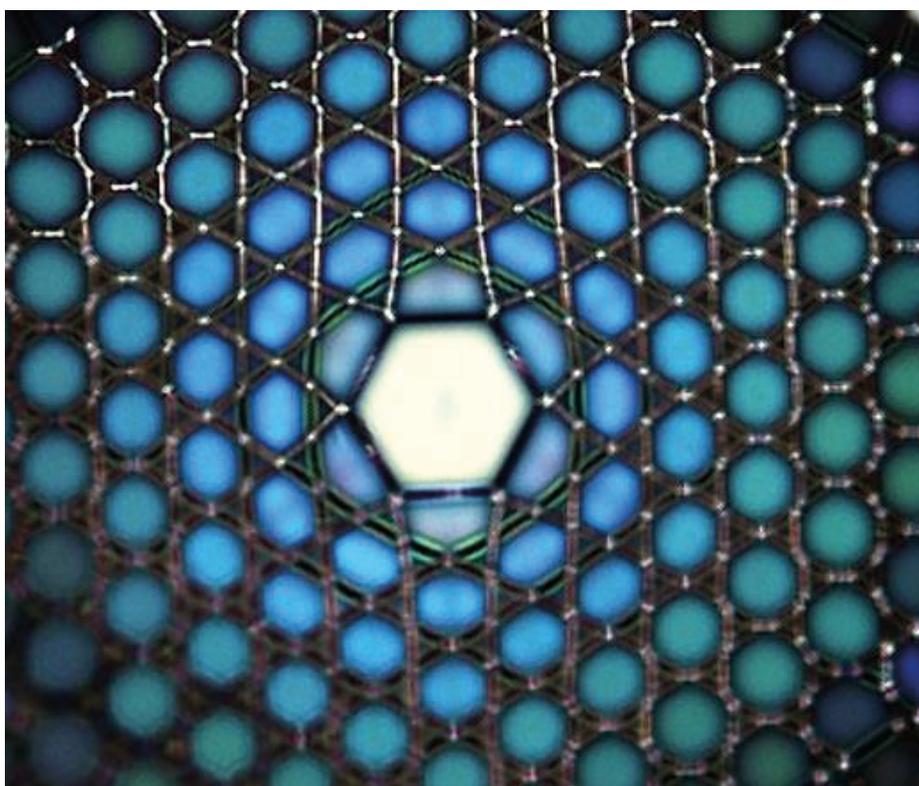
## Optofluidics group in NanoPhotonics



We warmly welcome **TIJMEN EUSER** as a new Lecturer whose research is closely linked to the Winton Programme for the Physics of Sustainability. Based in the NanoPhotonics Centre, his group uses hollow waveguides to study the interplay between optical, thermal, and fluidic forces on the nanoscale, and to probe chemical reactions in confined geometries. He writes:

Over the past years, my team at the Max Planck Institute for the Science of Light in Erlangen, Germany has shown that hollow-core photonic crystal fibres (PCF, see figure 1) act as excellent optofluidic waveguides that can be used to study highly-controlled light-matter interactions. The guidance mechanism in these fibres is based on interference, rather than total internal reflection, uniquely allowing light to be guided in microscale hollow channels with extremely low propagation losses [1].

When micro- or nanoparticles are inserted into the fibre, radiation pressure provided by the propagating modes can be used to optically trap and propel them along the hollow core. The waveguide geometry ensures that optical forces are well-defined at each position along the fibre, making it possible to measure precisely external influences on the particles. For example, by observing the particle dynamics in air-filled fibres, we discovered an optothermal trapping mechanism based on optically-driven thermal creep [2], a microscale version of the effect that causes Crookes' radiometer to rotate the 'wrong' way. Optically propelled particles can also be used as microscale 'flying particle sensors' that can map external quantities such as the electric field along the length of the fibre with a spatial resolution that is only limited by the size of the micro-particle (see figure 2) [3].



**FIG. 1.** Cross-sectional micrograph of a silica glass kagomé-type hollow-core photonic crystal fibre. The central core (white) has a diameter of about 20 micrometre.

In collaboration with chemistry groups at the Universities of Edinburgh, Warwick, and Erlangen-Nuremberg, we have also developed microscale optofluidic reactors based on liquid-filled hollow-core PCFs. A major advantage is that both the sample and light are confined to the same microscale channel, resulting in a maximized overlap and long interaction length. This system enables strongly enhanced photochemistry on sample

volumes that are five orders of magnitude smaller and at much reduced optical powers as compared to conventional systems [4]. We have also used hollow-core PCF in catalysis research, where the optical modes can be used to detect reaction products from catalyst nanoparticles deposited on the inner fibre surface [5].

Central to my research in Cambridge, I am establishing an *Optofluidic Microreactor*

Laboratory in the new Maxwell Centre, with the aim of developing novel methods for *in situ* spectroscopy in these systems. These fundamental studies are expected to have a strong impact on the development of new catalytic and photochemical systems for advanced applications such as water-splitting, photo-chemical reduction of trace pollutants, and the development of novel light-activated anti-cancer drugs. Our lab will also study waveguide-based optical manipulation of a range of different plasmonic and semiconductor nanoparticles, their resonant excitation, and their interactions. Our research makes full use of existing expertise in nanoparticle synthesis and spectroscopy, catalysis, and microfluidics, both at the Cavendish and across the School of Physical Sciences.

### A brief CV

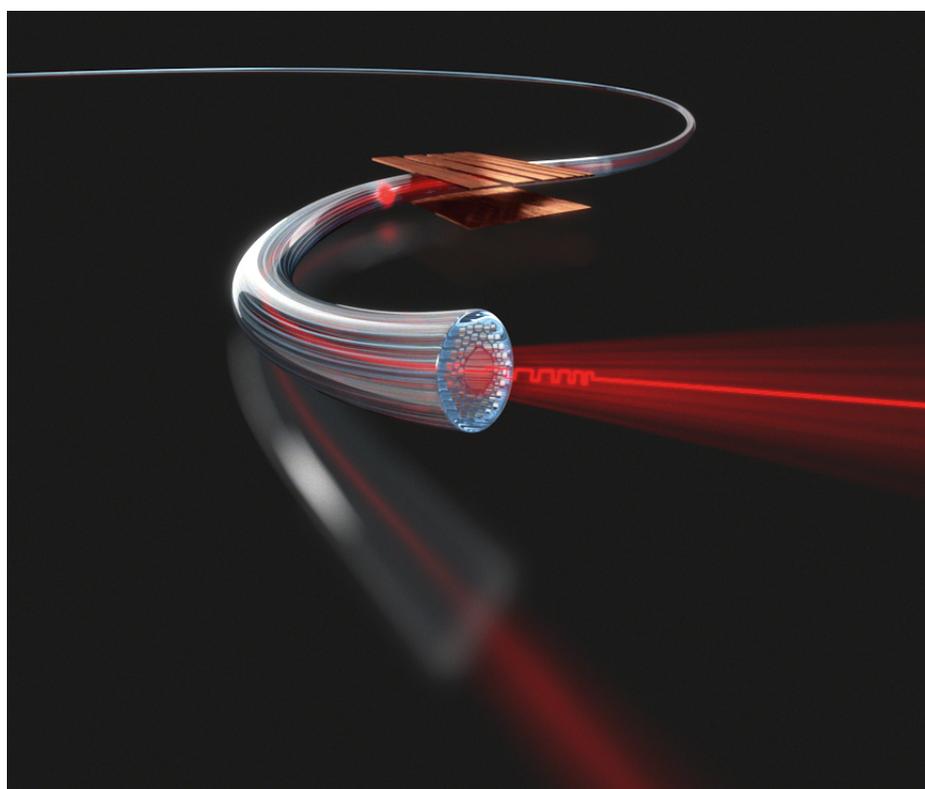
I received my undergraduate training at the University of Twente, a dynamic, research-oriented university in the east of the Netherlands. In my M.Sc. project, I studied how the growth direction and long-range order of colloidal photonic crystals can be controlled by patterning the substrate using a novel laser interference lithography process. In 2007, I completed my PhD research in ultrafast optical switching of photonic crystals in the Complex Photonic Systems group of Willem Vos at the MESA+ Institute for Nanotechnology at the University of Twente and the Institute for Atomic and Molecular Physics (AMOLF) in the Netherlands. By optically exciting free carriers in the semiconductor backbone of 3D Si-inverse opals and Si woodpile photonic crystals, we demonstrated that

the photonic band gap in such structures can be switched on or off on a 100 fs timescale.

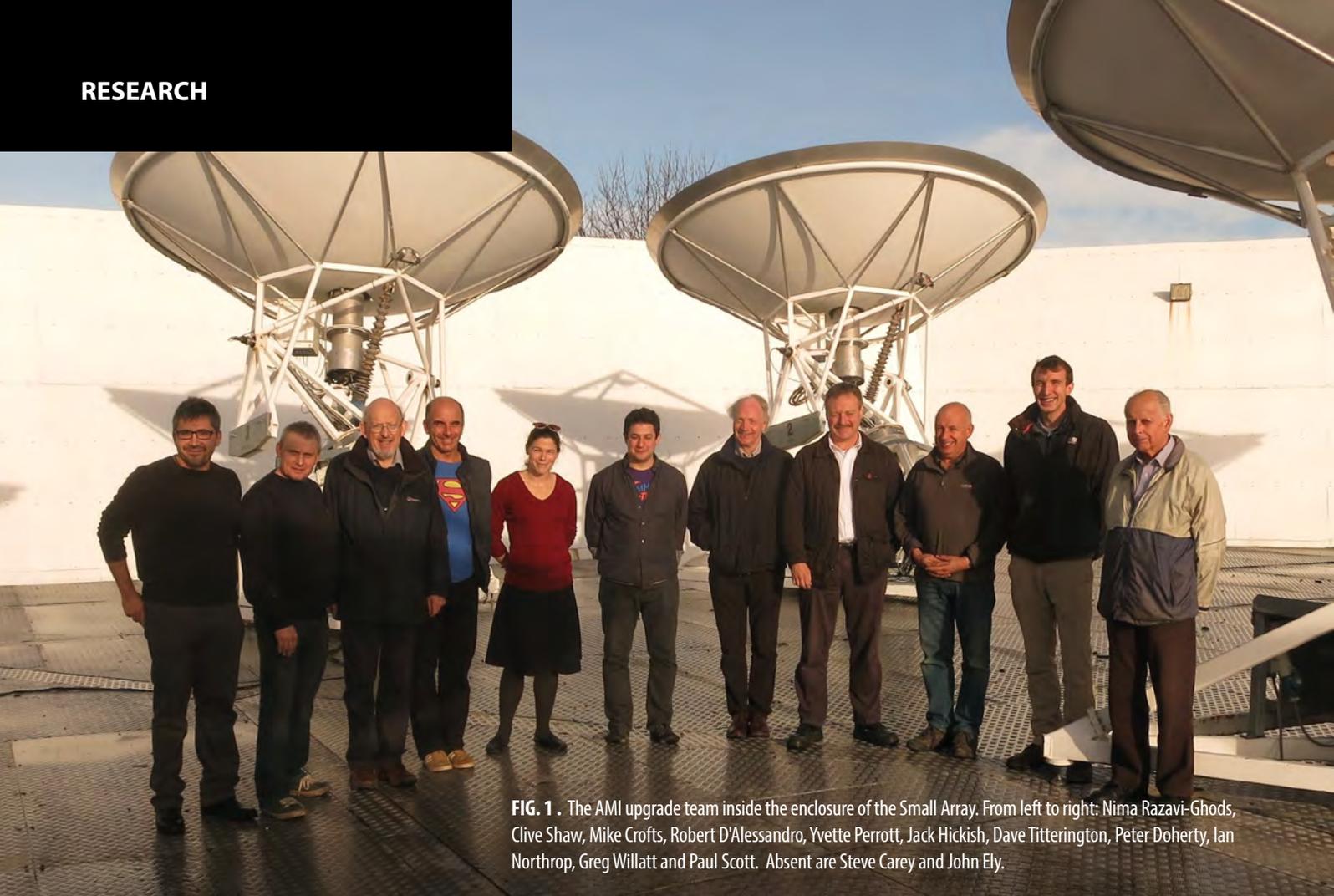
Subsequently, I joined the newly founded group of Philip Russell in Erlangen, Germany. In January 2009, our Photonic Crystal Fibre Science division became part of the new Max Planck Institute for the Science of Light (MPL). Over the past eight years, our team in Erlangen has developed a range of novel optical methods for advanced light-matter interactions in hollow-core photonic crystal fibres, as discussed in the main text.

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- [3] "Flying particle sensors in hollow-core photonic crystal fibre", D. Bykov, O. A. Schmidt, Tijmen G. Euser, and Philip St.J. Russell, *Nature Photonics* **9**, 461 (2015).
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**FIG. 2.** Schematic of a 'flying-particle' electric field sensor. An external electric field pushes the optically propelled microparticle out of its equilibrium position, thus modulating the amount of light transmitted through the fibre [3].



**FIG. 1** - The AMI upgrade team inside the enclosure of the Small Array. From left to right: Nima Razavi-Ghods, Clive Shaw, Mike Crofts, Robert D'Alessandro, Yvette Perrott, Jack Hickish, Dave Titterington, Peter Doherty, Ian Northrop, Greg Willatt and Paul Scott. Absent are Steve Carey and John Ely.

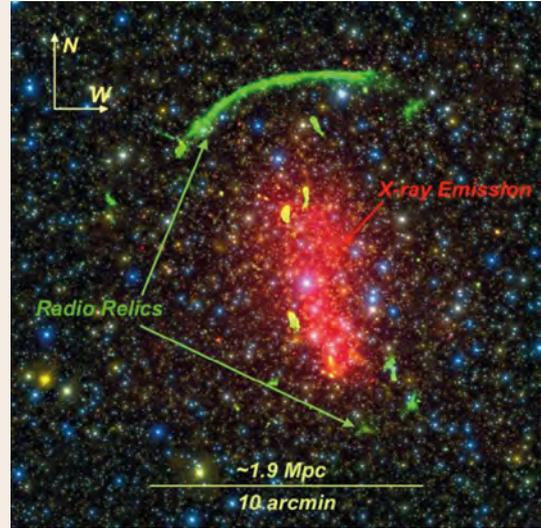
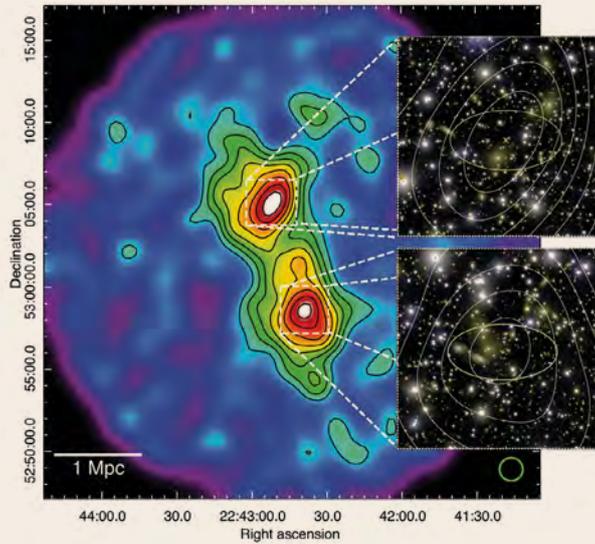
## The AMI telescope upgrade

**T**he Cavendish Astrophysics group, with financial support from the University of Manchester, has recently developed a high-speed digital correlator for the Arcminute MicroKelvin Imager (AMI) radio telescope at the Lord's Bridge Observatory. AMI is a dual array synthesis telescope consisting of two individually correlated arrays of receivers operating in the 12-18 GHz band. The Small Array (SA) comprises ten 3.7m paraboloid dishes in a compact configuration (Fig. 1) and is designed for observing source structures on angular scales of between 2 and 16 arcmin; the Large Array (LA), which was created by reconfiguring the eight 12.7m dishes of the original Ryle Telescope, is sensitive to structure on angular scales of approximately 0.5 to 5 arcmin and, for small diameter radio sources, has approximately ten times the sensitivity of the SA. The SA was designed primarily for studying clusters of galaxies by means of the Sunyaev-Zel'dovich (SZ) effect. The LA, observing concurrently with the SA, is used to measure the intensities of contaminating small-diameter sources.

The original correlator measured the signal in eight frequency channels over the 12-18 GHz band with limited capability for recognising and removing interfering signals. As a result, the sensitivity of the instrument was significantly reduced, particularly at low declinations, where interference from geostationary satellites could result in up to 90% of the data being rejected.

Starting in early 2014, an ambitious project was undertaken to build a digital correlator for the telescope based on existing Field Programmable Gate Array (FPGA) modules developed by the CASPER group at the University of California, Berkeley, aptly named ROACH (Reconfigurable Open Architecture Computing Hardware) boards. The primary goal of the project was to equip the telescope with a highly channelised digital correlator system providing over 500 times the number of frequency channels than the original system. This greatly improved the spectral response, allowing more precise elimination of interfering signals and overcoming many of the original limitations. The project required a highly optimised FPGA correlator design to be developed, which is currently the widest bandwidth correlator system being

**Imaging the Sunyaev-Zeldovich Effect in the cluster of galaxies CIZA J2242+5301N, also known as the 'sausage' cluster.**

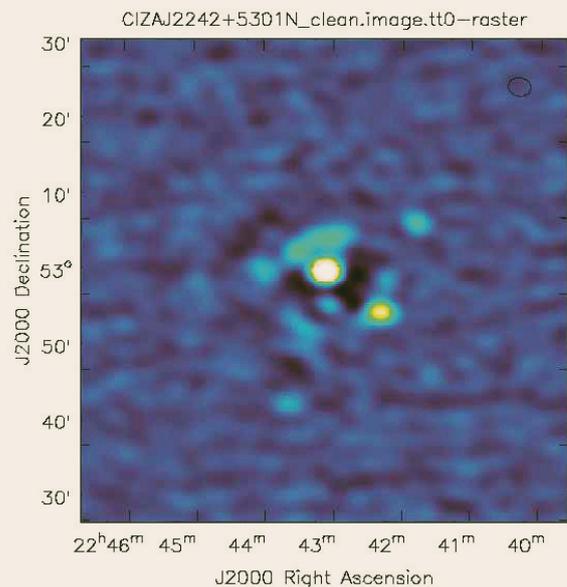


**(Left)** An optical image of two merging clusters of galaxies, the colour contours showing the smoothed galaxy luminosity density map of CIZA J2242.8+5301 based on cluster red sequence selection. **(Right)** the X-ray (red) and radio (green) images of the clusters. The X-rays delineate the distribution of hot gas, while the radio images show shocked material. Images courtesy of Huub Röttgering and his colleagues in the Merging Cluster Collaboration: Left from Dawson et al (2014) Astro-phy ArXiv 1410.2893v1 and Jee et al (2014). Astro-phy: ArXiv 1410.289v1

used on any radio telescope. The correlator, which fits into a single 19-inch rack, comprises ten (SA) or eight (LA) FPGA systems which communicate via a high-bandwidth Ethernet Switch. The internal data rate is close to 1 Tbit/s and, together, the two arrays produce some 250 GB of user data per day. The architecture and technologies used for the AMI correlator are very similar to those to be used in the international Square Kilometre Array (SKA) project which, when completed towards the end of this decade, will be the world's largest radio telescope.

Commissioning of the telescope is now almost completed and the instrument is being used to carry out further studies of clusters of galaxies, complementing data from the existing instruments, such as LOFAR and MeerKAT. A further exciting and unique capability of the instrument is for very rapid follow-up of transient signals detected by telescopes observing in other wavebands.

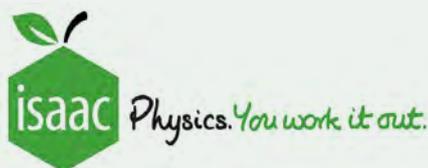
**NIMA RAZAVI-GHODS**



A recent image of the merging clusters made with AMI shows both the SZ effect (the black negative region in the centre), and the positive radio emission tracing the shock front seen in the above figure (right). The dark region in the centre corresponds to a 'hole' in the radio background emission caused by Compton scattering of the photons of the background radiation by the hot intracluster gas seen in the figure in the above right panel. (Courtesy of the Cavendish Laboratory).

# The Isaac Physics Project: A close run thing

Since the last edition of CavMag, Isaac Physics was shortlisted as one of the top 6 projects for outstanding digital innovation in teaching or research awards sponsored by the Times Higher Education. Unfortunately we didn't win but the Isaac Physics team were delighted to be shortlisted in such a strongly contested category.



## Isaac Physics user numbers soar

In CavMag14 we were delighted to report over 4000 users and nearly 600 teachers registered with the project. These numbers now pale into insignificance compared with the present registered numbers:

**Students:** 14,864

**Teachers:** 1,032

**Number of questions attempted:**

1,649,218

Students and teachers alike continue to provide us with very positive feedback that has been extremely helpful in continuing the development of the project. We are also very pleased with the positive comments we have received.

Our analytic tools also show that Isaac is becoming embedded into the school day

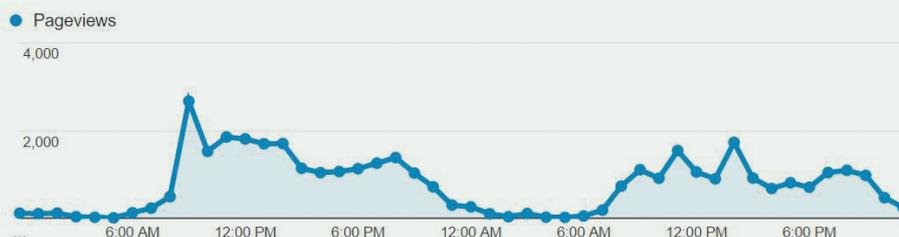


FIG. 1.

with students continuing to use Isaac for homework. A sample of pageviews for a two-day period are shown below (Fig. 1).

## New Features & Content

What's new in the technology?

- Touch enabled on-line Equation Editor
- Touch enabled on-line graph sketcher
- Online interactive tutorials

These are trial versions for users to test on their various desktop and mobile devices before we begin using this technology as a method of marking solutions to problems. Isaac physicists are running one hour online tutorials for teachers and students in the twilight hours after school to provide additional support and help in solving problems across our various topics and levels.

## New topics

The Isaac project began online in October 2014 with problem-solving questions in mechanics and mathematics across 6 levels of difficulty. With the help of an army of natural science undergraduates we have broadened our offer greatly to include waves, fields, circuits and chemical physics. The range of topics at different levels is shown in Fig. 2.

FIG. 2 (a). Physics Questions

| Topic            |                  | Level |   |   |   |   |   |
|------------------|------------------|-------|---|---|---|---|---|
|                  |                  | 1     | 2 | 3 | 4 | 5 | 6 |
| Mechanics        | Statics          | ✓     | ✓ | ✓ | ✓ | ✓ | ✓ |
|                  | Kinematics       | ✓     | ✓ | ✓ | ✓ | ✓ | ✓ |
|                  | Dynamics         | ✓     | ✓ | ✓ | ✓ | ✓ | ✓ |
|                  | Angular Motion   |       |   |   | ✓ | ✓ | ✓ |
|                  | Circular Motion  |       |   |   | ✓ | ✓ |   |
|                  | SHM              |       |   |   | ✓ | ✓ | ✓ |
| Waves            | Optics           | ✓     | ✓ | ✓ |   |   |   |
|                  | Superposition    |       | ✓ | ✓ |   |   |   |
|                  | Wave Motion      | ✓     | ✓ | ✓ |   |   |   |
| Fields           | Electric         |       |   |   | ✓ | ✓ |   |
|                  | Magnetic         |       |   |   | ✓ | ✓ |   |
|                  | Gravitational    |       |   |   | ✓ | ✓ |   |
|                  | Combined         |       |   |   | ✓ | ✓ |   |
| Circuits         | Resistors        | ✓     | ✓ | ✓ |   |   |   |
|                  | Capacitors       |       |   |   | ✓ |   |   |
|                  | General Circuits | ✓     | ✓ | ✓ |   |   |   |
| Chemical Physics | Thermodynamics   | ✓     | ✓ | ✓ | ✓ | ✓ | ✓ |

FIG. 2 (b). Maths Questions

| Topic    |                        | Level |   |   |   |   |   |
|----------|------------------------|-------|---|---|---|---|---|
|          |                        | 1     | 2 | 3 | 4 | 5 | 6 |
| Geometry | Vectors                |       | ✓ |   |   | ✓ |   |
|          | Trigonometry           | ✓     | ✓ | ✓ | ✓ |   |   |
|          | Shapes                 |       | ✓ |   |   |   |   |
| Calculus | Integration            |       |   |   | ✓ | ✓ |   |
|          | Differentiation        |       | ✓ |   | ✓ | ✓ |   |
|          | Differential equations |       |   |   |   | ✓ |   |
| Algebra  | Simultaneous equations | ✓     |   |   |   |   |   |
|          | Quadratics             | ✓     |   |   |   |   |   |
|          | Manipulation           | ✓     |   |   |   |   |   |
|          | Series                 |       |   | ✓ |   |   |   |

# Physics at Work 2015 and the Cambridge Colleges Physics Experience



September saw the 32<sup>nd</sup> annual **Physics at Work exhibition**, in which 20 demonstrators from research and industry gave presentations to nearly 2100 students and teachers from around Britain. The talks focused on the practical application of physics, showing how concepts learned in the classroom can be applied in complex real-world situations.

## 2015–16 Event examples and to come

The teacher and student workshops are major parts of the programme of activities carried out under the Isaac Physics project. Through partner teachers and institutions we are able to deliver activities across the whole of the UK. For updates and details of all our events, see <https://isaacphysics.org/events>

## Isaac Physics at the Cambridge Science Festival

The Isaac Physics project team will also be running two events as part of the **Cambridge Science Festival 2016**.

- **7:15pm–8:15pm, Friday 18<sup>th</sup> March – Churchill College** – Students and parents workshop (Dinner available to buy in Churchill College beforehand)
- **1–5pm, Saturday 19<sup>th</sup> March** – Cavendish Laboratory – As part of the Cavendish Laboratory's open afternoon we will be offering a **drop-in session for students** and a **bookable session for teachers**.

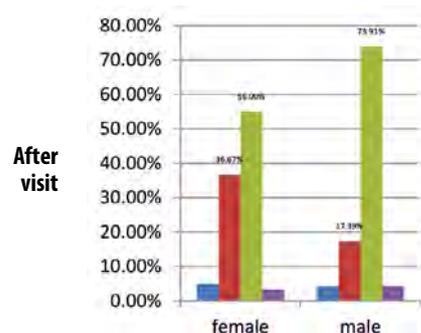
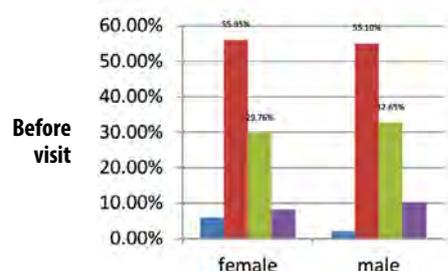
The talks were all rated positively, with the majority being rated over 5 out of 6 by teachers. Particular praise was given to the dynamic nature of the talks by young Researchers, their relevance to the taught curriculum, and the level of student interaction throughout the day.

Each year, students are asked to vote for their favourite demonstration. For the second consecutive year, the Biological and Soft Systems group won, narrowly beating groups from the Atomic Weapons Establishment, Maths Works, and Isaac Physics.

The **Cambridge Colleges' Physics Experience** has recently begun its fourth year. Feedback has already been positive, showing a significant improvement in the students' opinions of higher education, studying at Cambridge, and physics.

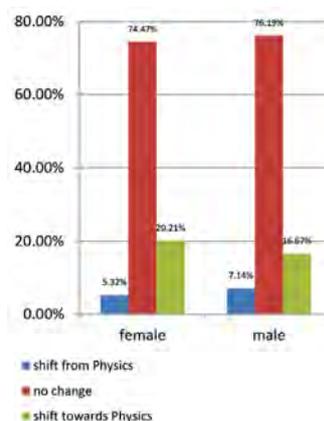
The end of year report for the 2014-2015 period has shown the positive effect of the CCPE events. The time spent in colleges and in the department helped to demystify Cambridge, placing it as an aspirational goal for students.

## Education and Training plans beyond age 18, Y11 group, November 2014/ March 2015



■ training beyond 18  
■ university  
■ Cambridge  
■ too early to say

The sessions also help to clarify students' opinion of physics at a university level; whilst some moved away from the subject once the level of mathematics and understanding required was made clear, the majority remained positive or shifted towards it.



■ shift from Physics  
■ no change  
■ shift towards Physics

## Uncovering Maxwell

**T**he essay on James Clerk Maxwell and the Michelson-Morley Experiment in CavMag12 was illustrated by the dark portrait painted by his cousin Jemima Blackburn, neé Wedderburn

(Fig. 1). Unfortunately, together with the famous painting of Maxwell and his wife, the portrait had been stored in unsatisfactory conditions in the Laboratory and both needed expert attention to restore them to their former glory. We had in mind the forthcoming opening of the Maxwell Centre and our wish that these might form a centrepiece for the new building. Consequently, restoration of the paintings was entrusted to the Hamilton Kerr Institute, the Conservation Department of the Fitzwilliam Museum. One of us (ATdS) was responsible for the various aspects of the restoration process.

To understand the creative process, both portraits were subjected to X-ray and infrared imaging to reveal any underpainting. The biggest surprise was the infrared image of the dark portrait of Maxwell (Fig. 2(a)). There was unmistakable evidence that the oil painting was an overpainting of the 'official' photographic portrait of Maxwell, a contemporary tinted version of which is shown in Fig. 2(b). The tell-tail signs are the identical folds in the sleeve to the bottom left of the images, the broad lapels and the waistcoat. Analysis of the paper on which the portrait was created indicated that it was a form of photographic paper.

The original photograph probably dates from the early years of Maxwell's tenure of Cavendish Professorship of Experimental Physics, 1871-79 and is in the style of a

formal Victorian portrait. The records in the Cavendish Laboratory indicate that the painting was part of a large bequest given to the Laboratory on the death of Maxwell's widow, Katherine Mary Dewar, in 1886.

Painting over a photograph was already a well-developed and established practice by that time (Ruggles, 1985), resulting from the close connections between photography and painting practice. Rapidly advancing photographic techniques became common aids to painting in the artist's studio.

Using photographs as substrates for painting, although sharing the same context of technical development and the desire for real-life likeness, differs from the contemporary fashion for tinted photographs, of which the photographic portrait of Maxwell is a fine example (Fig. 2(b)). Here the photograph has not been concealed but enhanced.

In the painted portrait of Maxwell, it is clear that the artist's intention was to use the photographic image as a guide from which to create her own personal interpretation of her cousin, using the image as an underdrawing or a guideline. In fact, in the finished portrait Jemima has slightly changed the orientation of the sitter's shoulders and his gaze and lips have different expressions when contrasted with other prints of the same photograph. She has also made Maxwell look quite a few years younger, with less grey hair than his true appearance in the photograph, presumably taken in this mid-40s.

The painting (Fig. 1) has sketchy brushwork and paint, executed in oils and applied quite thinly towards the edges of the image

and more thickly in the highlights of the face. Before conservation, the surface was very uneven with widespread blooming and blanching of the varnish layer, which did not extend to the very edges of the painting. The restoration involved surface cleaning to remove the blooming, retouching and the application of a new varnish layer. The painting was refitted with low-reflective glass, with an acid-free card layer separating the painting from the acidic backboard. The result is a new gleaming portrait of Maxwell, the romantic hero revered by so many of us (Fig. 3).

Similar investigations were made of the portrait of Maxwell and his wife, also attributed to Jemima Wedderburn, although not with certainty (Fig. 4). The discoveries were not as dramatic as in the case of the portrait of Maxwell alone. An infrared scan revealed a tree to the right of the picture which has been painted out. The varnish was a natural resin which had degraded to a yellow colour which gave the painting an unnatural yellow hue which obscured the painting's original colour. As a result of the treatment, the painting has been restored to its original vibrancy, a touching joint portrait of Maxwell and his wife with their dog Tobi who was Maxwell's constant companion, even during his daily visits to the students in his new Laboratory.

**ALICE TAVARES DA SILVA AND  
MALCOLM LONGAIR**

**REFERENCE:** Ruggles, M., 1985. Paintings on a photographic base, *Journal of the American Institute for Conservation*, **24**, 92-103.

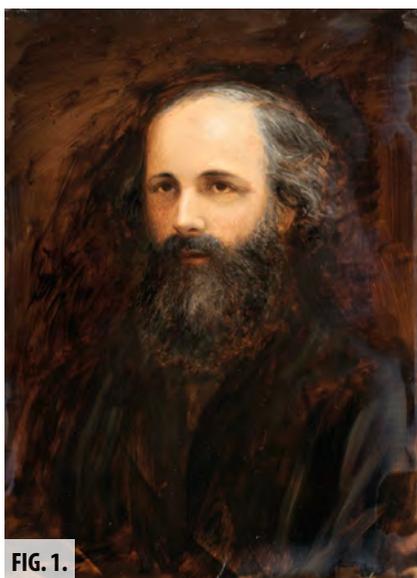


FIG. 1.

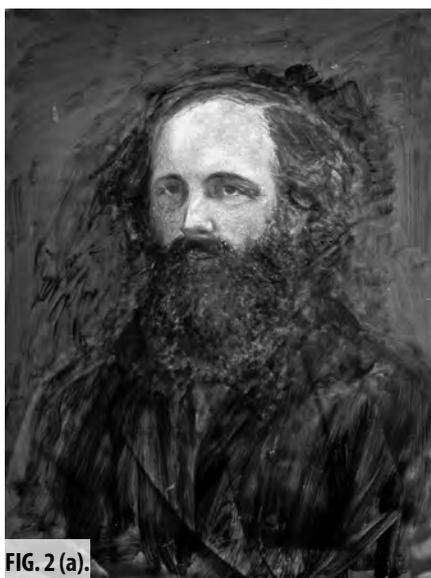


FIG. 2 (a).

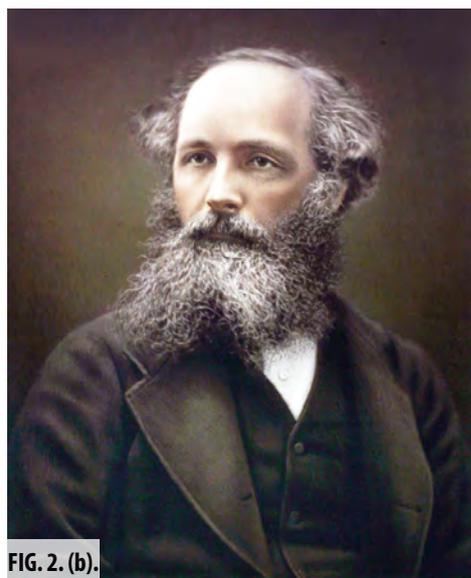


FIG. 2. (b).

**FIG. 1.** The unrestored portrait of Maxwell painted by his cousin Jemima Wedderburn (Courtesy of Hamilton Kerr Institute, University of Cambridge and the Cavendish Laboratory).

**FIG. 2. (a)** An infrared image of the Maxwell Portrait (Courtesy of Hamilton Kerr Institute, University of Cambridge). **(b)** The tinted photographic portrait of Maxwell (Courtesy of the Cavendish Laboratory).

**FIG. 3.** Portrait of Maxwell after surface cleaning, retouching and re-varnishing. (Courtesy of Hamilton Kerr Institute, University of Cambridge and the Cavendish Laboratory).

**FIG. 4.** Portrait of Maxwell and his wife after the removal of the original varnish, cleaning and retouching (Courtesy of Hamilton Kerr Institute, University of Cambridge and the Cavendish Laboratory).

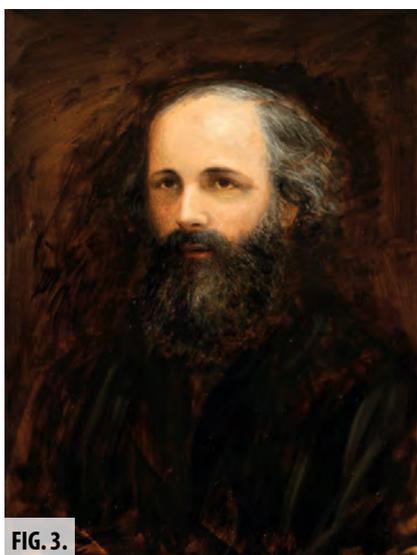


FIG. 3.



FIG. 4.

## Winton Symposium 2015

**The 4<sup>th</sup> Winton Symposium was held at the Cavendish Laboratory on 28<sup>th</sup> September 2015, on the topic of Green Computing. Richard Friend, Director of the Winton Programme, explained that previous symposia have explored areas where there is considerable headroom for advances and this is particularly the case for computing and more broadly Information and Communications Technology (ICT) where current technologies are often orders of magnitude below fundamental physical limits. This year's Symposium explores both advances in materials and what we can choose to do with the additional computing power, both to use it efficiently and to drive more energy efficient living.**

**Mike Lynch (pictured, left)**, founder of Invoke Capital and Autonomy, explained how energy efficiency was not really considered in the early days of computing, but now the power and cooling needs of data centres have become a major operating cost. This has led to the development of new architectures with 'hot' and 'cold' servers. Moving data to the source of power is also becoming a viable proposition. From a signal processing and pattern recognition perspective more computing power will lead to markedly improved results. Data will be available in greater quantities and in different forms spurred on by the proliferation of sensors for the 'Internet of Things' and wearable technologies. The ability to fuse these different forms of data, either locally stored or in the cloud, will provide contexts that can improve how we optimise a host of activities, from crop growth and speech recognition to route guidance systems. In conclusion, building in sustainability from the outset by combining new materials, architectures, and regulations will enable us to benefit from the additional computing power.



**Andy Hopper**, Head of the Computer Laboratory at the University of Cambridge, in his talk, 'Computing for the Future of the Planet', considered what we can do better in the computing areas and how this can have societal benefits. His talk covered four main topics; the first was 'Green Computing' where improvements in efficiency of the digital infrastructure had led to stabilisation of the total energy consumption. The second he refers to as 'Computing for Green' where the availability of sensors and data can be used to do things more efficiently. An example is the use of industrial control in manufacturing where the efficiency of automation can be improved by more accurate tracking of components. With the increase in dependence on computing and automation, the assurance of the computing needs to keep pace. One aspect is the ability to keep a history of the data and its transformation; protocols are being developed that allow an audit trail to be kept with relatively low overhead cost. The final topic was wealth creation, with reference to the developing world, where mobile phone coverage is >75% and provides opportunities for people to bypass intermediate steps. An example is the growth of Massive Open Online Courses (MOOCs), which are providing education that can really change peoples' lives.



**Krisztián Flautner**, head of ARM's Internet of Things (IoT) Business Unit, explained how IoT was based on the convergence of devices, computing and connectivity. Over a number of years the underlying technology has been developing such that sensors and microprocessors can be made so cheaply that the time is right for numerous opportunities with a strong business case. An example is a street lighting project with GE Lighting where new lights with smart metering provided significant savings, with payback in only 1-2 years. The project is being extended to parking and traffic management providing the backbone of a smart city infrastructure. The volumes for IoT processors are staggering, with 5 billion units per year expected by 2020 and double-digit growth in all sectors. For this emerging field the metrics for evaluation will need to evolve. Whereas for mobile communication the key parameters were performance, energy and price, trust and scale have to be included. IoT will generate vast quantities of data, which will only be trusted if ownership, access and privacy issues have been resolved. This will require control of the data and establishment of standards across the globe. The scale of the IoT will require many different partners to work together to make the number of products needed that connect together, as well as finding sufficient software



**Linda Nazar (pictured, centre)**, from the University of Waterloo, discussed the recent development of batteries in her presentation 'New Materials and Approaches for Advanced Electrochemical Energy Storage'. She explained that storage is more important today than ever before, with integrated systems required to meet our growing demand for large and small scales of energy. Grid level storage that exploits renewable energy sources and big computers and data centres require MWh, whereas Wh and even lower are required for small devices and sensors to power the 'Internet of Things'. The other large driver for storage is electric vehicles that require kWh storage. These applications have very different requirements in terms of performance and cost points and so tailored solutions will need to be developed. Li-ion batteries have played an important role, since the fundamental work by John Goodenough in 1990 and their subsequent commercialisation by Sony. A key metric is the gravimetric capacity that has shown steady progress to current values of 200- 225 Wh/kg, which is close to the limit for these types of batteries. A range of other battery technologies have been developed with improved performance; one example is based on  $\text{LiFePO}_4$  which has been commercialised for vehicles, as well as large grid storage. The chemistry is rather complex with the crystals forming surface conducting networks of  $\text{Fe}_x\text{P}$  that provide conduction of charges and in addition the creation of solid solution phases that promote fast transport of ions. For grid storage more abundant materials are being considered, including using Na instead of Li, as well as divalent ions where weight is less of an issue. Another important area is the exploration of solid state electrolytes, which have a number of benefits including being less hazardous, easier to package and make into thin films and prone to longer cycle life; factors particularly important for portable batteries.

developers. The latter may be addressed by encouraging web designers and young people to learn how to program, which is being supported by ARM through supplying, free to children, the BBC 'micro:bit'. Krisztián closed his talk by describing the rich ecosystem of players that is being built that encompasses all aspects from hardware to the cloud that will enable people to build the appropriate IoT solutions.

**Luca Cardelli**, from Microsoft Research and the University of Oxford, in his talk 'Molecular Programming' introduced a totally different way of doing computing using biological materials. From a hardware perspective traditional computing has made components smaller and smaller, instead if we start with molecules, the problem becomes how can we build systems. In nature this bottom-up approach is routinely achieved through self-assembly with materials pre-programmed to fit to each other, forming well defined structures that arrange and replicate to form highly complex systems. Luca gave examples of how nano-control devices can be constructed that combine sensors and actuators which can all be formed from DNA, and described how logic circuits also based on DNA could be built. Although the field is still in its infancy and it will take some time to find practical solutions, it is growing rapidly and the promise is amazing.

**Hideo Ohno (pictured, right)**, from Tohoku University described how very large scale integrated (VLSI) circuits are prevalent in so many aspects of our lives. In his talk 'Nonvolatile VLSI made possible by Spintronics', he described some of the trends and challenges we face to meet growing demand for circuits and how these can be addressed. Power consumption has grown as devices become more complex with more active components, but an equally important factor is the increase in the standby power due to higher leakage currents. Another challenge is that of interconnection delay, associated with systems having separate logic and memory components and information having to be passed between the two, which causes delay and consumes power. The concept he proposed is to move from volatile memory to non-volatile memory which reduces considerably the standby current losses. Non-volatile memory such as flash are already available. These and other alternatives, however, have issues related to operational voltage and endurance; spintronics devices are the only viable choice that satisfies all the requirements. Devices based on magnetic tunnel junctions, are widely available, where device resistance is a function of the alignments of the spins of two layers separated by an insulator. Other devices based on switching with spin polarised currents spin-transfer torque (STT) and are being developed. These can operate without a magnetic field by using the spin Hall effect from an antiferromagnetic layer and have high switching speeds. Through precise control of materials and layer thicknesses to sub-nanometer accuracy, it has been possible to make spintronic devices with high performance. He concluded by proposing a new paradigm in VLSI where circuit designers and process engineers would work together to integrate spintronic logic and memory which will provide solutions that are both greener and have higher performance.

## The Cavendish Graduate Conference 2015



The Cavendish Graduate Student Conference has been running annually for the past seven years. It provides an opportunity for graduate and undergraduate students to share their own research and to learn about the range of research their peers are carrying out. The tradition is to have two invited talks - a keynote address to inspire the student community, and a presentation by the freshly-minted winner of the Abdus Salam prize. The conference is largely organized for the students by the students. Ankita Anirban, Hippolyte Astier, Nandan Gokhale and Peter Townsend made up the 2015 Organizing Committee.

The Conference began with a swift introduction by Ben Gripaos, wearing his Graduate Training Co-ordinator hat. Then, the majority of the day was devoted to 18 contributed talks and 24 posters. All the research groups in the Department were represented. Next came the Keynote Lecture. We were delighted and honoured that Jocelyn Bell Burnell was able to return to Cambridge and tell

us *A Graduate Student's Story*. The central thread, the story of Jocelyn's discovery of pulsars, came across as a victory for dedication and perseverance, a message from which everyone can take heart. The final presentation of the day was the Abdus Salam prize talk, a lucid and relaxed tour through the Quantum Theory of a Perfect Fluid delivered by David Sutherland.

Now all that stood between the audience and the buffet (apart from hundreds of secondary-school students in the Pippard foyer) was the prize-giving. Presenting the awards were Jocelyn Bell-Burnell, and Rodney Johnston representing BP. The judging panel was made up of members of the Organizing Committee, joined by presentation-skills aficionado Chris Haniff for the poster judging. Hannah Stern of Optoelectronics won the Best Talk prize; Miguel Arratia of High Energy Physics and David Arvidsson-Shukur of Thin Film Magnetism secured the runner-up talk prizes. The Poster prizes went to Ping Liang Tan in the area of Astrophysics and Adam Smith in the theory of Condensed Matter. Feedback showed that the audience

was very pleased with the quality of the presentations, both oral and poster. I certainly learnt a great deal about other students' research. The high quality of the contributions to this year's event ought to spur even more enthusiasm across the Department for future Graduate Conferences. For the graduate students, honing their presentation skills is mandatory for whatever career they pursue after the PhD and the more encouragement and friendly criticism they receive from their more experienced colleagues, the more valuable the day becomes.

**PETER TOWNSEND**

**IMAGES, left:** Jocelyn Bell Burnell; **right:** presentation of the Abdus Salam Prize © Kelvin Fagan.

## John Shakeshaft, Radio Astronomer 1929–2015



**J**ohn Shakeshaft was one of the second generation of physicists who joined the fledgling Radio Astronomy Group in 1952 to carry out a PhD under Martin Ryle's supervision.

The discipline of radio astronomy scarcely existed at the time. Martin had joined the Cavendish Radio Group immediately after the War and begun the long process of disentangling the nature of the radio sky. The existence of discrete sources of radio emission was soon established and by the time John joined the Group it was known that some of these were associated with rather remarkable astronomical objects, for example, exploding stars such as the Crab Nebula and what appeared to be colliding galaxies.

When John joined the Group, the second generation of radio interferometers, optimised for surveys of the radio sky, had been designed. His task was threefold: to complete the electrical construction of the four-element interferometer, to analyse the survey records, almost all of which had to be done by hand, and to interpret the results of the survey. What became known as the Second Cambridge (2C) Survey of Radio Sources was published in 1955 with John as first author.

To say that the results of the survey caused a furore in the radio astronomical and cosmological communities would be an understatement. The survey showed that there were many more faint sources than expected in non-evolving cosmological models. Battle was joined, not only with the proponents of Steady State Cosmology, but also with the radio astronomers from Sydney who could not reproduce the Cambridge results. It turned out that the intensities of the faintest sources in the 2C survey had been overestimated because of the phenomenon of 'confusion', the presence of faint unresolved sources in the beam of the radio telescope when brighter sources were observed.

There followed another survey in which John played a major role, the Third Cambridge (3C) Survey carried out with the same 2C interferometer with twice the angular resolution to minimise the effects of confusion. This catalogue contained only 470 sources and became the precursor of the definitive survey of bright sources in the Northern Sky. The excess of faint sources was still there, but not to the extent inferred from the 2C survey.

Subsequently, he made important observations of the polarisation of the radio emission from the Galaxy and extragalactic radio sources and also the lowest frequency

measurements of the Cosmic Microwave Background Radiation, following its discovery in 1965 – the latter confirmed the thermal nature of the radiation..

From the late 1950s onwards, John played a key support role in fostering the many activities of the Radio Astronomy Group. He kept track of all the data on radio sources as new surveys appeared, as well as combing the literature for all the papers relevant to radio astronomy and the new disciplines of high energy astrophysics and astrophysical cosmology.

A particular service was his editing of radio astronomy papers in the course of their preparation. All of us became used to draft papers coming back from John with more red ink than the contents of the papers themselves. The annoying thing was that he was right! He found his ideal role as editor of Monthly Notices of the Royal Astronomical Society, although it was strange to many of us how the unbelievable chaos of his room in the Laboratory contrasted with the punctiliousness of his editing.

He is fondly remembered by many of us as an excellent colleague who provided essential support to our research activities. His good humour never deserted him.

**MALCOLM LONGAIR**



John Shakeshaft (right) and Dennis Bly in the old Radio Astronomy Electronics Laboratory in 1974.

## Who Was A.W. Scott?



**FIG. 1.** Professor A.W. Scott (centre). Courtesy of the Roderic Bowen Library and Archives, University of Wales Trinity Saint David.

One of the more embarrassing items in the introduction to the Scott lectures has been our admission that we really knew very little about Professor A.W. Scott, after whom the lectures are named. Clifford Will, who delivered a spectacular series of Scott lectures in October 2015 to celebrate the centenary of Einstein's discovery of the field equations of general relativity, urged us to try harder. The result has been a huge advance in A.W. Scott studies, thanks to the efforts of colleagues and particularly Sarah Roberts, archivist at the Roderic Bowen Library and Archives, University of Wales Trinity Saint David, and John Hodgson, Manuscripts and Archives Manager at the John Rylands Library at the University of Manchester.

Arthur William Scott was born in Dublin in 1846. He was educated at Trinity College Dublin where he obtained his BA in 1868. His considerable abilities in mathematics and science were recognised by his distinction of being Senior Moderator and Gold Medallist in

Mathematics, and Senior Moderator and Gold Medallist in Experimental and Natural Science. He was awarded his MA degree in 1868. In 1872, he was appointed Phillips Professor (Science) at St David's College, Lampeter (Fig. 1). In the same year, he published the only paper he is known to have written. It is reproduced in full in Fig. 2.

St. David's College, Lampeter was then a small Theological College in Central Wales. As recorded in *The Cambrian News and Merionethshire Standard*, of 23 October 1885,

'[In 1840] Mr Thomas Phillips, London, founded six new scholarships and six years afterwards established a new professorship of physical science, now so ably held by Mr. A. W. Scott, M.A., late mathematical scholar of Trinity College, Dublin. This, with a Welsh professorship which was subsequently founded raising the number of professors to five.'

The one unique feature of the college was described in Whitaker's Almanack of 1894.

'Lampeter has the exceptional privilege of conferring degrees B.A. and B.D., and has been affiliated to the Universities of Oxford and Cambridge.'

A further link of Scott's with Oxford and Cambridge was the fact that, until relatively recently, Oxford and Cambridge did not recognise degrees from any other University, except Trinity College Dublin, Scott's *alma mater*.

Scott was a Fellow of the Physical Society of London, a Fellow of the American Association for the Advancement of Science and Fellow of the Institute of Physics. He was renowned as a great traveller and seized every opportunity to travel to conferences abroad. He was among the members of the party which attended the 1914 New Zealand meeting of the British Association for the Advancement of Science, other delegates including the Astronomer Royal Frank Dyson and John Nicholson, who discovered the law of the quantisation of angular momentum before Niels Bohr. Scott was a participant in the large 1899 meeting held in Pembroke College, Cambridge to celebrate the 50<sup>th</sup> Anniversary of George Gabriel Stokes' accession to the Lucasian Chair of Mathematics.

In 1908, Scott was chairman of the Lampeter Gas Company and was Mayor of Lampeter 1910–11. He was tempted to apply for the chair of Physics at Melbourne, Australia, but in the correspondence with his former Lampeter colleague Professor Tout, then at Manchester University, Scott was concerned that the Melbourne position was very demanding with a considerable amount of experimental work. He regarded this as his weak point since he did not want to spend time 'fiddling in the Laboratory'. It would also restrict his ability to go on his extensive trips abroad. A delightful

A FINE display of shooting stars was observed here on Wednesday, 27th inst. I first noticed them at 7.20 P.M., Greenwich time, and watched them till about 8, when the sky became obscured. They were occasionally seen again till 9.30. When first observed they appeared to radiate from the zenith, and to be more numerous towards the north-west and south-west; many passed over the constellation Cygnus. A. W. SCOTT  
St. David's College, Lampeter, Nov. 30

FIG. 2. The only known paper by A.W. Scott: *Nature*, 5 December 1872. (Thanks to Malcolm Perry).

portrait of Scott in his college rooms at St. David's was published in the *S. David's College Magazine* of 1923 where it is recorded that he was 'the smallest of the dons'. The author goes on to recount how,

'Turning towards his table, I began to wonder whether the Professor had just returned from a visit to Tutankhamen's tomb, for there were some thirty or forty albums of assorted shapes and sizes, lying upon it, while numerous curios and pictures adorned the mantelpiece and walls. The Professor explained, he had collected them from the uttermost parts of the earth, in particular, his furniture was from Lilliput, where he made a sojourn while on a tour round the world.'

On his departure from the visit, the author states that

'In showing me out he introduced me to his iron steed, which on several occasions had borne him across the Alpine regions.'

In his will, Scott was very generous to Cambridge University. In the *Cambridge University Reporter* for 1926-7, Page 1058, there is an entry entitled, *Bequest of Professor A.W. Scott 10 May 1927*.

The Vice-Chancellor begs leave to publish the following letter which he has received from the Right Honorable Lord RIDDELL.

Dear Mr. Weekes,

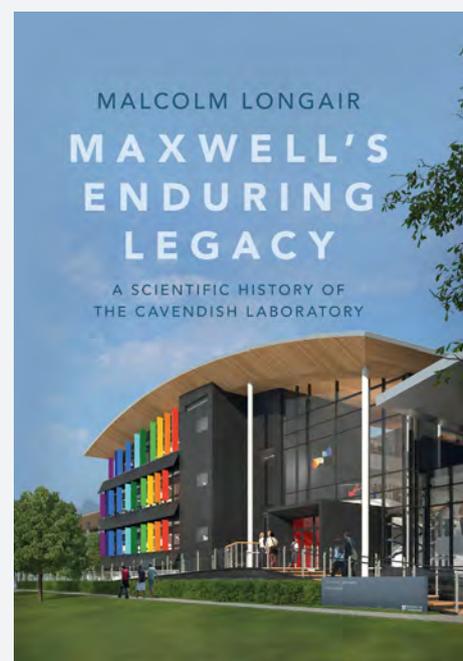
My friend the late Professor A.W. Scott of LAMPETER who died on 7th March has left £7000 to Cambridge University for the furtherance of Physical Science and also one third of the residue of his estate, which will probably amount to some £4000, for a similar object. I hope to send you a cheque shortly.

Sincerely yours, RIDDELL.

This gift, equivalent to about £600,000 in today's currency, was gratefully accepted by the Regent House on 20 May 1927. He also left a bequest of £500 to the National Gallery which was used to buy Rubens' painting, 'The Watering Place' and £250 to the British Association for the Advancement of Science.

Scott could not have known of the glittering list of Scott Lecturers which began with Bohr (1930), Langmuir (1931), Debye (1932), Geiger (1933), Heisenberg (1934), Hevesy (1935), Appleton (1936), De Haas (1937), Siegbahn (1938) and Blackett (1939). We are delighted that the lectures have remained at this distinctly elevated level.

**MALCOLM LONGAIR**



Your editor's new book 'Maxwell's Enduring Legacy: A Scientific History of the Cavendish Laboratory' will be published by Cambridge University Press in the Spring of 2016. The history spans the period from the mid-19<sup>th</sup> century to the present day – it is about 660 pages in length. A special discounted price will be available to readers of CavMag. Details will be provided in CavMag16 (July 2016).



**IMAGES ABOVE, LEFT:** Keith and Annette Mathews cutting the cake. **RIGHT:** Keith with three of the Laboratory Superintendents under whom he served. From left to right Brian Goshawk, Peter Bystricky, Keith and Peter Norman.

## The place will never be the same without ...

We wish **Keith Mathews** a long and happy retirement after more than 37 years in the Laboratory. He joined as an electrician and then progressed through maintenance supervisor to Head of Maintenance. He has done a wonderful job in ensuring that the Laboratory continued running smoothly on a 24/7 basis. This often involved working into the wee small hours to avert catastrophes such as running water in electrical conduits, floods, power outages and so on. His splendid, cheerful approach will be missed by all his many friends in the Laboratory.

## Many congratulations to



**Zoran Hadzibabic** for the award of the **2016 Holweck Medal and Prize of the French Physical Society**

**and the Institute of Physics** for his 'outstanding experimental achievements in the control of ultracold quantum degenerate gases'.



**Harry Cliff** for the award of the **2015 Institute of Physics HEPP "Science in Society Prize"** for

his 'work as Curator and Head of Content for the successful "Collider" exhibition and other outreach work with the Science Museum, CERN, and the Cavendish Laboratory'.



**Alex Mitov** for the award of an **ERC Consolidator Grant** with the title 'New level of

theoretical precision for LHC Run 2 and beyond'.



**ABOVE:** Gil Lonzarich (centre) with Suchitra Sebastian (left) and Siddharth Saxena (right).

## Quantum Physics Prizes

**Gil Lonzarich** (centre) with **Suchitra Sebastian** (left) and **Siddharth (Montu) Saxena** (right) on the occasion of the award of the 2015 Kamerlingh Onnes prize to Gil on 24th August 2015 at the 11th International Conference on Materials and Mechanisms of Superconductivity in Geneva. The prize was awarded in recognition of his 'visionary experiments concerning the emergence of superconductivity for strongly renormalized quasiparticles at the edge of magnetic order'. It is awarded every three years at the M2S Conference, for outstanding experiments which illuminate the nature of superconductivity.

**Suchitra** has also been awarded a 2015 Philip Leverhulme Prize which involves a donation of £100,000 to be spent on whatever activities will best promote her future research. In addition, she has won the 2015 Brian Pippard Prize of the Institute of Physics Superconductivity Group, which is awarded 'to a scientist working in the UK who has made a significant contribution to the field of superconductivity in the last few years.'

Many congratulations to both.

## New Appointments

We welcome the following new members of Department:

**Tijmen Euser** Lecturer, Nanophotonics Group (see pages 12–13)

**Christina Potter** Early Career Lecturer, HEP Group

**Chris Braithwaite** Early Career Lecturer, SMF Group

**Maxine Flynn** HR Operations & Projects

**Renata McLeod** Departmental Finance Advisor

**Surayya Khan** Graduate Education Manager

**Emel Kus** Cavendish III Project Manager (seconded from Estates Management)

**James Sharkey** Content Development/Programmer, Rutherford Schools Project

**Umberto Lupo** Content Development/Programmer, Rutherford Schools Project

**Emma Clark** NanoDTC Administrator

**Lorraine Irle** Cleaner

## Leavers

Best wishes to those who are leaving the department:

**Clare Dickinson**, Registrar

**Alan Clarke** Group Administrator, TCM

**Emily Boyd** Administration Assistant, Graduate Office



## 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](https://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](https://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](https://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 at:

[www.phy.cam.ac.uk/development](https://www.phy.cam.ac.uk/development)

### » 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](https://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 ([mssl1000@cam.ac.uk](mailto:mssl1000@cam.ac.uk)) or Gillian Weale ([departmental.administrator@phy.cam.ac.uk](mailto: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** ([mssl1000@cam.ac.uk](mailto:mssl1000@cam.ac.uk)) or **Andy Parker** ([hod@phy.cam.ac.uk](mailto:hod@phy.cam.ac.uk)), who will be very pleased to talk to you confidentially.

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