



# CAVMAG

News from the Cavendish Laboratory



Astronomy meets Atmospheric  
Science at the SPECTRO-ICE  
Workshop

Gil Lonzarich's 70th Birthday  
Materials Discovery by Computer  
Designing the Centaurs of the Quantum Realm  
Unravelling the Chain Fountain  
Sam Edwards 1928–2015  
Derek Vonberg 1922–2015

Celebrations come in different forms. We celebrate the lives of those who have passed away and those who have reached conspicuous birthdays. The death of Sam Edwards leaves an irreplaceable gap in the intellectual life of the Laboratory. As the eighth Cavendish Professor, his influence on the research programme was immense and he was largely responsible for its present structure. Derek Vonberg was only three years in the Laboratory immediately after the War, but he and Martin Ryle essentially created the discipline of radio astronomy in Cambridge.

Gil Lonzarich reached his 70th Birthday and a spectacular meeting of his colleagues was an enormously happy occasion. Peter Littlewood gives some impression of Gil's totally original approach to research – but be warned, Peter's piece stretches your editor, even after he had written a box about Fermi Liquids for non-initiates, such as himself.

Malcolm Longair

INSIDE

Concepts and Discovery in Quantum Matter	2
Gil Lonzarich and the remarkable robustness of the Fermi liquid	4
Materials Discovery by Computer	6
Designing the Centaurs of the Quantum Realm	8
Astronomy meets Atmospheric Science at the SPECTRO-ICE Workshop	10
Unravelling the Chain Fountain	12
Administering the Laboratory	13
The Cavendish Research Staff Committee	14
Quantum Mechanics for Everyone	16
Sam Edwards 1928–2015	18
Derek Vonberg 1922–2015	20
Outreach	21
Cavendish News	23



Cover image: Lenticular clouds over Rothera, Antarctica. Courtesy Gavin Burns.

# Concepts and Discovery in Quantum Matter



In Honour of Gil Lonzarich's 70<sup>th</sup> Birthday, a remarkable conference entitled *Concepts and Discovery in Quantum Matter (CDQM)* was held in the Cavendish Laboratory on 14-16 July 2015. On this memorable occasion, a galaxy of the pioneers and leaders in the field paid tribute to Gil and described research at the frontiers of the discipline ■

**IMAGES CLOCKWISE FROM ABOVE:** The Conference Photograph before dinner in Trinity College; Gil Lonzarich; The CDQM organisers with Gil and Geri Lonzarich. Left to right: Montu Saxena, Cheng Liu, Suchitra Sebastian, Geri Lonzarich, Gil Lonzarich, Sian Dutton, Mike Sutherland, and Malte Grosche.

Photography by Cheng Liu and Xiaoye Chen



# Gil Lonzarich and the remarkable robustness of the Fermi liquid



**PETER LITTLEWOOD**, former head of the Cavendish Laboratory and now Director of the Argonne Laboratory in the USA, pays tribute to Gil Lonzarich's unique contributions to experimental and theoretical condensed matter physics research on the occasion of Gil's 70th birthday. Your editor took the liberty of including a box in which some of the more technical terms, which are bread and butter concepts in these remarkable areas of fundamental research, are explained.

**Fermi liquid theory** is a phenomenological theoretical model of *interacting fermions*, such as electrons, that describes the normal state of most metals at sufficiently low temperatures. Starting with a non-interacting fermion system, or a *Fermi gas*, the interaction is turned on slowly. Landau argued that the ground state of the Fermi gas would *adiabatically* transform into the ground state of the interacting system. As the strength of the interaction is turned up, the spin, charge and momentum of the fermions corresponding to the occupied states remain unchanged, but other properties, such as their mass, magnetic moment etc. are *renormalized* to new values. There is therefore a one-to-one correspondence between the *elementary excitations of a Fermi gas system* and a *Fermi liquid system*. In the context of Fermi liquids, these *excitations* are called *quasiparticles*. *Landau quasiparticles* are long-lived *excitations* with a lifetime  $\tau$  that satisfies  $1/\tau \ll \epsilon_p$ , where  $\epsilon_p$  is the excitation energy and  $p$  is the momentum. The interaction between the particles of the many-body system does not need to be small and so applies equally to *strongly-correlated electrons*.

**W**hile Landau's theory of Fermi liquids had been well established by the 1970's as a formal theory of strongly interacting Fermi liquids, the experimental basis of the theory's validation was almost entirely in terms of thermodynamic properties and response functions, especially their specific heats, susceptibilities, and conductivities. Even in the best studied system, helium-3, the quasiparticle at the core of the theory was elusive and invisible. From the point of view of many theorists, Fermi liquid theory with its set of parameters seemed merely a phenomenology that would eventually be displaced, or at least validated, by a 'proper' theory that would at a minimum enable the Fermi liquid parameters to be calculated, and more ambitiously the generalised dynamical response functions. But little attention was paid to the reality of the quasiparticle excitations themselves.

This viewpoint, though not universal, was probably enhanced by the emerging

successes of density functional theory that uses electronic bands merely as a formal prop to construct the density. Especially in strongly correlated systems, one has learned to mistrust electronic band structure. And even in weakly correlated semiconductors, despite the successes of constructing the ground state energy, the excitation spectra could only be reconstructed by ad hoc resummations of diagrams with the best of the methods justified by appeal to sum rules and some careful choice of the level of self-consistency.

Fermi liquid theory teaches us that in a metal, quasiparticles are long-lived at the chemical potential, and for simple metals that had been long tested. In the 1970's condensed matter physics began to explore 'heavy fermion' systems, where the hybridisation of strongly correlated core levels together with itinerant valence electrons had been seen to behave as a 'heavy Fermi liquid', where for example the Pauli paramagnetic susceptibility and the electronic specific heat can be enhanced by a factor of a thousand from a simple metal - yet the material is a good metal. Since the behavior is inherited from the physics of

the Kondo lattice, where one expects very strong self-energy renormalisations close to the Fermi energy, could it still be true that the Fermi liquid phenomenology is valid? To attack this problem required standard fermiology, of which Gil was already a known master from his work on weak ferromagnets, but nonetheless, when I and others saw the 1987 report of the Fermi surface(s) of UPt<sub>3</sub>, we were stunned that the experiment had even be attempted, since the effective mass controls the relative amplitude of quantum oscillations. It remains an extraordinary *tour-de-force*.

The paper [1] has a concise conclusion.

"Cyclotron orbits have been observed which correspond to extremal areas of the Fermi surface ... [and] cyclotron masses ranging from 25 to 90  $m_e$ . The effective mean free path of the carriers ... is between 1000-2200 Å. The experimental Fermi surface areas are not inconsistent with recent local density band calculations. The observed cyclotron masses are,

**1)** L Taillefer et al, JMMM 63&64, 372-6 (1987); L Taillefer and GG Lonzarich, Phys. Rev. Lett. 60, 1570 (1988)

“ With Philippe Monthoux now at Cambridge, the two of them produced what may still be the best practical phenomenological theory of spin-fluctuation-mediated superconductivity. ”



however, in all cases much greater than predicted by the local density band models, by a factor which is, within the experimental error, of the same order of magnitude as the ratio of the experimental to the band calculated linear coefficient of the heat capacity.”

A hallmark of Gil and his group - exquisite samples and exquisite precision of measurement - provide a robust conclusion. The Fermi liquid has proved hard to kill off, though he has been trying.

Soon after, Gil presented a review paper [2] about the connections between the spin-fluctuation response in  $\text{Ni}_3\text{Ga}$  and  $\text{Pr}$ , which also have enhanced masses, and the heavy fermion response in  $\text{UPt}_3$ . This turned out to be a very prescient connection between itinerant magnetism and heavy fermion physics.

$\text{UPt}_3$  was known to be an unusual superconductor and, for someone who was well-versed in weak itinerant magnets, the connection of superconductivity to magnetism would surely be of interest. Around this time, Gil was clearly also warming up to the idea of tuning materials through pressure [3], which would be especially effective in narrow band materials. This was followed up with work on  $\text{UPt}_3$ ,  $\text{MnSi}$ , and other materials. In 1993, at the SCES conference the first [4] of a series of studies of the pressure-induced critical behavior of itinerant magnets was presented – what we now call *quantum critical phenomena*. The blockbuster paper that used pressure

studies to connect the quantum critical point of magnetism to unconventional superconductivity in  $\text{CeLn}_3$  and  $\text{CePd}_2\text{Si}_2$ , together with the canonical phase diagram [5], appeared a little later – already with a sophisticated theoretical view around the topic.

With Philippe Monthoux now at Cambridge, the two of them produced what may still be the best practical phenomenological theory of spin-fluctuation-mediated superconductivity [6], which explained the advantages of antiferromagnetic (AF) fluctuations in 2D (for d-wave) versus either 3D AF systems, or ferromagnetic systems. Not inconsequentially, it made a good case for AF fluctuations in the cuprates as the dominant mechanism and, while there is no rigorous calculation that can be performed on such a strongly correlated system, there is much to be said for this point of view, especially in light of our emerging understanding of the pseudo-gap state. For a while, though, a somewhat disconcerting result was the discovery of superconductivity inside the ferromagnetic regime of  $\text{UGe}_2$  [7], which was uncomfortable. As we have learned more about unusual metamagnetism in this material, we have become more comfortable with it in connection with the antiferromagnetic counterparts.

It is a strange observation that while the heavy fermion systems show enormous renormalisations of their properties, they are still Fermi liquids, and it is here that we have the most convincing evidence for itinerant magnetic fluctuations driving both superconductivity, and – at the critical point – the controlled appearance of a non-Fermi liquid. The cuprates are more enigmatic – partly of course because a very bad metal emerges out of a robust localised quantum magnet, so there is no reason to trust weak-coupling-inspired theory – but also, as it turns out, because some interference was being run by other phenomena. When first observed by nuclear magnetic resonance, the peculiar underdoped regime of the

cuprates was first called a ‘spin gap’; when it emerged that all Fermi surface properties were suppressed, some of the earliest and most systematic data coming from John Cooper and John Loram in the Quantum Matter group, it was recast as a ‘pseudo-gap’; and lately with the discovery of charge order in this regime, it should really be called a gap, plain and simple. The most illuminating studies of the Fermi surfaces of underdoped cuprates are emerging – as they always have – from quantum oscillation measurements, both in Cambridge and elsewhere [8], but the Lonzarich legacy is in evidence. There will continue to be many theories for both the pseudogap state and for superconductivity, but it is comforting that we can now conclude that the underdoped cuprates are indeed Fermi liquids, just with small Fermi surfaces. However, at the ‘optimal’ composition, evidence remains that they are not.

Looking forward, I think ferroelectric quantum critical phenomena [9] are emerging as a new topic: there is extra physics here as a result of long-range interactions involving Coulomb and elastic strain, and there is another enigmatic superconductor to understand in  $\text{SrTiO}_3$ .

It has long been observed that one of the greatest services that the principal can do for his or her biographer is not to write too much. Gil is refreshing in that he publishes only when he has something to say, though sometimes not even then. I also note his propensity for presenting great discoveries in conference papers, which of course reflects his discursive, didactic and referential attitude to the science community. In contrast, when junior authors are more in control, the papers are of course published in *Nature*. His group also represents the ultimate in care, precision, self-containment, and methods. As a student, one grows the sample, builds the apparatus, takes the data, and does the theory. As well as the science, the group is pushing the community in techniques for high pressure, high magnetic fields, and novel refrigeration schemes. It’s a reflection of the style of Pippard, and of Shoenberg, and Gil Lonzarich is the worthy inheritor of their mantle ■

2) GG Lonzarich, JMMM 70, 445 (1987)

3) JD Thompson, Z Fisk and GG Lonzarich, Physica B 161, 317 (1990)

4) C Pfeleiderer et al, Physica B 199, 634 (1994)

5) ND Mathur et al, Nature 394, 39 (1998)

6) P Monthoux and GG Lonzarich, Phys. Rev. B 59, 14598 (1999); Phys. Rev. B 63, 054529 (2001)

7) SS Saxena et al, Nature 406, 587 (2000)

8) N Doiron-Leyraud, et al., Nature 447, 565–568 (2007); SE Sebastian et al., Nature 511, 61 (2014)

9) S E Rowley et al., Nature Physics 10, 367 (2014)

# Materials Discovery by Computer



**ANDREW MORRIS** is a Winton Advanced Research Fellow working in the Theory of Condensed Matter Group. He explains how materials can be studied using the most advanced computer algorithms, among the challenges being the discovery of new materials to increase the storage capacity of batteries.

**T**homas Edison's approach to optimising the electric light-bulb was to test every filament material he could think of. 700 materials and a number of years later, he settled on carbon [1].

This 'trial and error' approach traditionally plays a large part in the discovery of new materials. For each idea, a new material must be synthesised then categorised before it can be tested which is slow, difficult and expensive. My group performs high-throughput computations which accelerate the materials discovery process by suggesting, then screening, new materials. This allows us to ask 'what if?' without the time and expense of manufacturing and categorising samples.

Understanding a new material at the atomic level is an important first step in predicting its properties. For example, diamond and graphite comprise the same carbon atoms but are wildly different only because of their different *crystal structures*. Diamond, with atoms arranged in a three-dimensional network is the hardest substance known whereas graphite, with atoms arranged as stacked 2D sheets, flakes easily from the end of a pencil.

Our computational structure prediction technique combines quantum mechanics, which tells us how each atom bonds to its neighbours, with a global optimisation technique called *Ab Initio Random Structure Searching* (AIRSS), which was developed in

**1)** Tungsten was the optimal filament but it was not possible to mass produce it at the time.

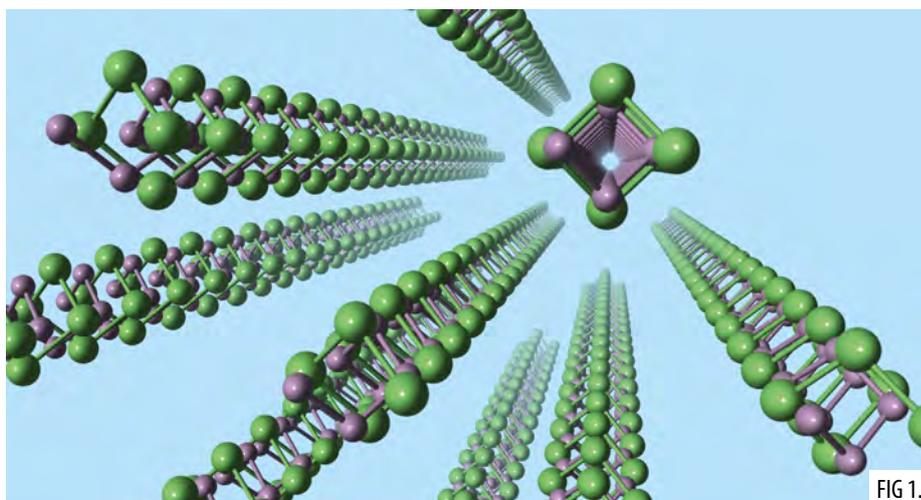


FIG 1.

Cambridge by Chris Pickard and Richard Needs. The AIRSS philosophy is simple: known parameters are used as search constraints and unknown variables are randomised. This turns out to be a very efficient way of sampling the multi-dimensional configuration space of possible crystal structures (Fig. 1). We can generate tens of thousands of plausible candidate materials within a few days using local, university-wide and national supercomputers.

The final piece of the puzzle is screening - calculating useful properties to find the best candidates for experimental analysis. We call this 'first principles spectroscopy' as it is analogous to the experimentalist putting their newly-made samples into an X-ray diffractometer, NMR spectrometer or electron microscope. With colleagues from Oxford and UCL, my group develops the code OptaDOS for predicting such spectra ([www.optados.org](http://www.optados.org)). Now with the search space greatly reduced, instead of Edison's 700 candidate

materials, we have the most promising five (say) to be synthesised by experimentalists. The final step is to take what has been learned from the experimental verification and use it to suggest areas of the search space for further AIRSS searches.

## Lithium-Ion batteries

A large part of the group's work is concerned with one of the most important technologies of the age, the lithium-ion battery. Traditional lithium-ion batteries, the sort that are currently in your mobile phone, have an anode made of graphite. It stores lithium atoms between its sheets. Silicon is the next wonder material for lithium-ion batteries, having a theoretical capacity some 10 times greater than the current graphitic anode. There are, however, many obstacles to be overcome such as anode pulverisation, irreversible lithium losses and huge volume changes, before they can reach their full potential.

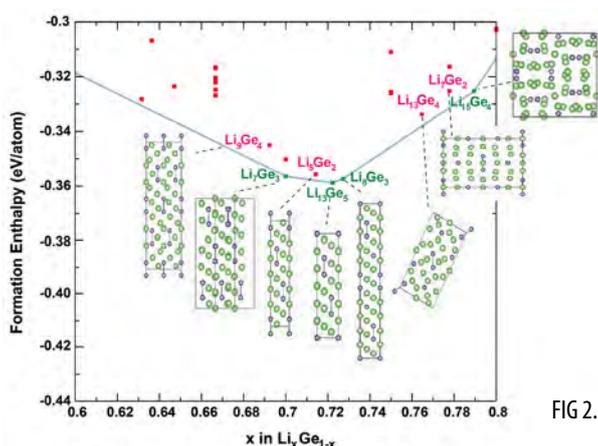


FIG 2.

FIG. 1. Infinite Li-P double helices discovered using computational structure prediction. Phosphorous atoms are shown in grey and lithium in green.

FIG. 2. Phase diagram of the computed Li-Ge system. The accessible structures at room temperature are those on the grey tie line, or just above it. These structures comprise (grey) Ge-Ge “dumbbells” in a sea of (green) lithium atoms. As lithium is added the dumbbells gradually separate from each other, over the ranges  $\text{Li}_9\text{Ge}_4$  to  $\text{Li}_5\text{Ge}_3$ , which experimentally is seen as a continuous shift of the Li NMR spectrum.

FIG. 3. The hydrogen/silicon defect in bulk silicon. This  $\text{Si}_i\text{H}$  complex sits in the hexagonal site and the silicon forms 6 weak bonds to neighbouring silicon atoms. (Hydrogen and silicon atoms are in white and yellow respectively).

Forming silicon nanowires is one way of overcoming these huge volume changes on charging but irreversible losses that ‘use up’ lithium still remain. Using our computational methods we aided the experiential chemists in Clare Grey’s Group in the Chemistry Department and were able to hint at why this hysteresis in such materials still forms [1].

Beyond the cutting edge is germanium, which perhaps does not have such a large capacity as silicon but has a much higher ion conductivity, hinting at much quicker charge times than silicon, at the same time having higher capacities than graphite. We predicted several new phases of the Li-Ge system, which were then verified by Grey’s group (Fig. 2).

### Point-defects

Perfect crystals in all three dimensions are hard to find, whereas real crystals usually contain flaws such as point defect impurities. These defects can drastically alter the properties of a material. Without point defect doping no semiconductor microchips would function and rubies and sapphires would have no colour. Over the last few years we have pioneered using the AIRSS method for the prediction of point defects in solids [2]. We have recently turned our attention to how hydrogen interacts with lithium in silicon batteries. We showed that the hydrogen present in silicon breaks silicon bonds and may make it easier to charge silicon anodes (Fig. 3).

We predicted the native defects in zirconolite, a synthetic rock used for high-level nuclear waste encapsulation. Simulation is essential

for such materials, since we cannot perform experiments over their expected lifetime of thousands of years. We predicted the most important oxygen defects. Furthermore, using the He nucleus as a model for the  $\alpha$ -particle, we calculated barrier heights of helium migration and showed that it was unfavourable for helium to cluster at the concentrations studied. Gas bubble formation in these materials would cause cracks to form in their casings leading to environmental nuclear contamination.

### The Future

What I enjoy most about computational structure prediction is the adventure – we never know what we will find next. Whilst looking for new phases in the Li-Si system we found perfectly flat layers of silicon which we predict to be stable at modest pressures. 2D systems are a recent hot topic due to the excitement surrounding graphene. During the Li-P project we came across Li-P clusters

comprising simple double helices. Follow up papers by other groups have compared them with DNA [3]. Unexpectedly, whilst looking for lithium defects in silicon, we found a new type of defect, which we called a Zintl defect, which actually solved a 30-year-old riddle of an unknown phase seen in experiments. These are a few of the highlights. Our database holds hundreds of thousands of new structures still to be understood and I am confident that AIRSS will uncover many more surprises in the future ■

### References:

- [1] *Revealing lithium-silicide phase transformations in nano-structured silicon-based lithium ion batteries via in situ NMR spectroscopy*, K. Ogata, E. Salager, C. J. Kerr, A. E. Fraser, C. Ducati, A. J. Morris, S. Hofmann and C. P. Grey, *Nature Comm.* 5 3217 (2014), DOI:10.1038/ncomms4217.
- [2] *Hydrogen/silicon complexes in silicon from computational searches*, Andrew J. Morris, Chris J. Pickard and R. J. Needs, *Phys. Rev. B* 78 184102 (2008), DOI:10.1103/PhysRevB.78.184102.
- [3] *Inorganic Double Helix Structures of Unusually Simple Li-P Species*, Alexander S. Ivanov, Andrew J. Morris, Konstantin V. Bozhenko, Chris J. Pickard and Alexander I. Boldyrev, *Angew. Chemie Int. Ed.* 51 33, 8330-8333 (2012), DOI:10.1002/anie.201201843.

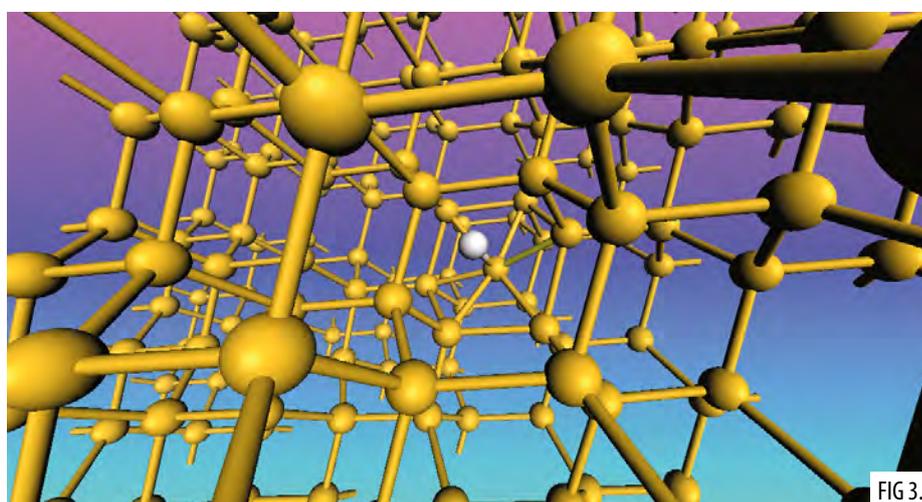


FIG 3.

# Designing the Centaurs of the Quantum Realm

METE ATATÜRE

**G**reek mythology is bursting with interesting characters and Centaurs are no exception. They are part horse part human and so can run as fast as horses and have the cognition of humans. They are temperamental and feisty characters, but a few of them like Chiron were distinctly wise, as well as powerful. The origins of Centaurs are not really well known. While it could be simply the wild imagination of a storyteller, it is also quite possible that the Centaur concept might be dated back to the first exposure of the Minoan Aegean communities to the horse-mounted nomad warriors. What a disruptive idea it must have been for its time to come up with hybrid mounted soldiers that can simultaneously surge like horses and fight like men!

Since the beginning of the 21<sup>st</sup> century we have witnessed a merger of quantum mechanics and information science for proof-of-principle demonstrations that highlight the outstanding capabilities of quantum

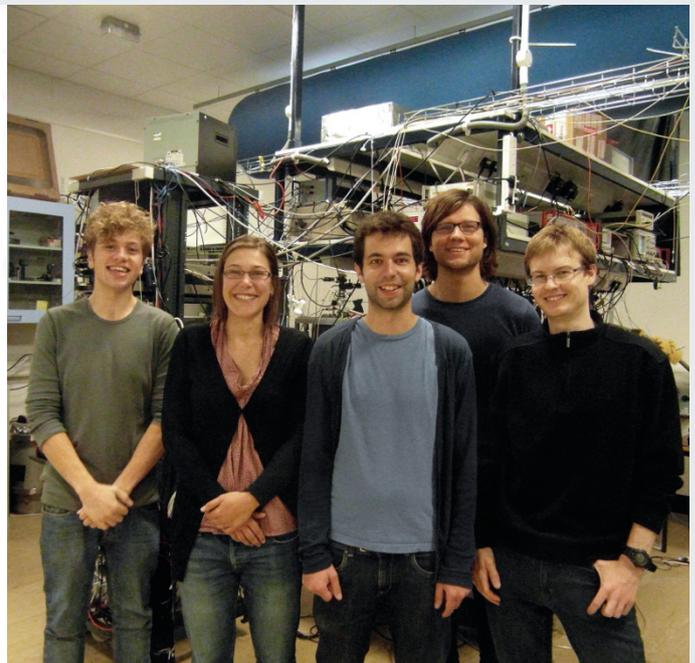
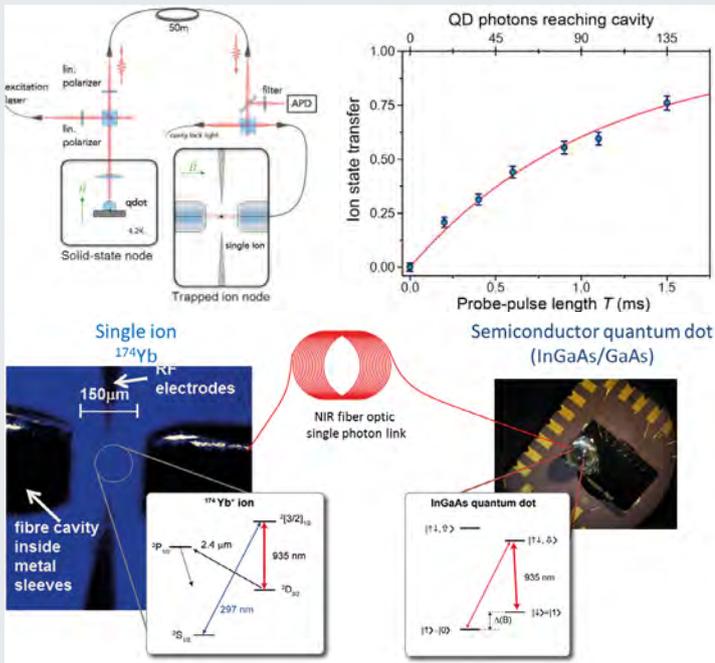
algorithms, quantum communication protocols and quantum sensor platforms. The state-of-the-art is based on modest processing units comprising only a handful of quantum bits (qubits) combined with prototype versions of communications and sensing systems. Trapped ions, superconducting systems, photons and spins in solids all possess attributes favourable for a number of applications and are being investigated worldwide with a number of other candidates. One common issue, however, is that scaling up the existing systems to large scales in a brute force approach faces serious technical, if not fundamental, obstacles. Each qubit candidate has shown its unique range of strengths and challenges. The general consensus is that there is no single physical system superior on all accounts to others in the quest for quantum technologies. For example, solid-state systems such as confined spins in optically active quantum dots offer high-speed gate operations, as well as the possibility of scalable architectures using

established techniques of nanofabrication. They suffer, however, from limited spin coherence times due to the inherent solid-state environment. In contrast, trapped ions have been used for quantum information storage and processing with long coherence times, but a huge amount of work and probably new concepts will be required to scale this approach up to much larger numbers of qubits and faster operations.

Enter the core concept behind the Centaur: an alternative approach is to create a hybrid quantum hardware system, where different tasks, such as the memory and the processing, are implemented separately by different physical systems, taking advantage of the distinct features of different physical qubits. In an example of a hybrid quantum processor, information would be stored for long times in an (atomic) memory with long coherence time, and temporarily swapped onto (solid-state) gate qubits for fast processing, thus combining the benefits of both systems. The swap operation can be done using flying (photonic) qubits, but this requires a coherent and low-loss interconnect between the physical qubits, so that faithful quantum state transfer can be realised. The quantum interconnects can then be used to create distant entanglement between the nodes. These could facilitate teleportation of quantum information throughout the network, which is required for long-distance communication via quantum repeater technology.

To this end, a joint research team led by Mete Atatüre and Michael Köhl in the Atomic, Mesoscopic and Optical Physics group (AMOP) of the Laboratory took on two key challenges to realise a hybrid quantum network: the ability to link two fundamentally different physical systems





- quantum dot spins and trapped ions - through a common optical interface and demonstrate a swap operation by flipping the internal state of the ion conditional on the internal state of the quantum dot spin. The semiconductor chip that contains the quantum dot spins is cooled down to liquid helium temperature (-270 °C) and a combination of laser pulses, electrical gates and magnetic fields is used to control the quantum state of the spin qubit. In another room across the hallway of the Rutherford building, a single ytterbium atom is ionised and trapped inside an ultrahigh vacuum chamber and accessed optically using a state-of-the-art fibre-based optical cavity. The two rooms are connected by 50-metre long optical fibres in order to deliver single photons from one node to the other. Figure 2 illustrates the key elements of this interconnection between the two physical systems.

In the experiment a quantum dot spin generates a stream of single photons at 935-nm wavelength, which are then sent down the long optical fibre between the two laboratories and into the optical cavity hosting the trapped ion. The ion is initially prepared in a particular quantum state and is ready to absorb the photons from the quantum dot at exactly the same wavelength. Once this absorption process takes place, the ion instantly changes its internal quantum state. The single photons

carry the information on the quantum state of the electron spin and so the transfer of the ion internal state is actually conditional on what the internal state of the electron spin in the other room was, thereby establishing a single-spin-single-photon-to-single-ion connection between the two quantum systems. The results were published in Physical Review Letters earlier this year [Meyer et al., *Phys. Rev. Lett.* **114**, 123001 (2015)].

The achievement of this first hybrid and distributed quantum network comprising single quantum entities presents a significant paradigm shift from the current direction of quantum information processing. While the constellation of state-of-the-art research capabilities in quantum-dot spins and trapped ions was arguably unique to Cambridge until very recently, more and more attention is dedicated to hybrid systems worldwide and progress with other physical systems have started to emerge. There are also numerous exciting directions for the near future: arbitrary quantum states can be transferred between different nodes regardless of the physical system they contain and the whole network can be increased in a modular fashion. One key challenge for all quantum network realisations is that they tend to be depressingly slow. In these experiments only five out of a million single photons trigger an internal state change of the ion, but most of

the limitations can be solved with relatively straightforward improvements. The more important limitation is the in/out efficiency of the photonic interface and if that can be solved it will also be possible to surpass the scalability threshold for such networks – but the competition is heating up. There is still a long way to go and many wonderful challenges to overcome, but we are a step or two closer to figuring out the components for the development of the ultimate Centaur of the quantum world ■

**LEFT:** A Centaur is a composite creature in Greek mythology that can move as fast as a horse, but have cognitive capabilities as advanced as a human, a hybrid concept bringing together the strengths of both species. *Image: Detail from an Attic white-ground black-figure lekythos located at the Metropolitan Museum of Art (New York City) photographed by Marie-Lan Nguyen.*

**CENTRE:** (top-left) Illustration of the hardware layout of the experiment. The quantum dot system is linked to the trapped ion system via a 50-metre long optical fibres. (bottom) Close up images of the two nodes: the chip containing the quantum dot spins and the single ion trapped inside a fibre-based optical cavity in ultrahigh vacuum. (top-right) The internal state of the ion is changed by single photons emitted by the quantum dot spin.

**RIGHT:** The AMOP research team working on this project: Rob Stockill, Claire Le Gall, Hendrik Meyer, Matthias Steiner and Clemens Matthesen. Other colleagues from Paris (FR), Bochum (DE) and Sheffield (UK) also joined forces and contributed to the success of this project. Photo courtesy of C. H. H. Schulte.

# Astronomy meets Atmospheric Science at the SPECTRO-ICE Workshop



**EMMA TURNER** and **STAFFORD WITHINGTON** summarise the exciting possibilities of applying advanced technologies developed for astronomical purposes to the study of the atmosphere and climate of our planet.

**T**he Quantum Sensors Group at the Cavendish Laboratory is working with British Antarctic Survey (BAS) and the Department of Applied Mathematics and Theoretical Physics (DAMTP) to explore how technology developed for astronomy can be used to address key challenges in observational atmospheric science. The collaboration, known as SPECTRO-ICE, grew out of the CAMbridge Emission Line Surveyor (CAMELS) project (CavMag Issue 11, pages 20-21): a prototype instrument funded by the STFC to use submillimetre-wave superconducting chip spectrometers on the new Greenland Telescope to measure the  $^{12}\text{CO}$  and  $^{13}\text{CO}$  gas content of distant galaxies. Many other technologies, such as heterodyne SIS receivers, HEB mixers, phase-locked local-oscillator sources, and long-wavelength gratings have been developed by astronomers for high-resolution spectroscopy and interferometry over the range 100GHz to 2THz, but surprisingly little of this technology has yet found its way into atmospheric science. Whereas submillimetre-wave astronomers regard atmospheric line and continuum absorption as a major nuisance, atmospheric scientists welcome these data to study atmospheric emissions. In fact, submillimetre-wave telescopes are not able to observe for considerable fractions of the time because the atmosphere is in the way, and even when they can observe, most of their focal planes are unused.

The SPECTRO-ICE consortium held a one day workshop, 'New Frontiers in Submillimetre-Wave and Far-Infrared Atmospheric Science'



FIG 1.

at the Møller Centre in Churchill College on 10th February 2015 to gather ideas on how technology developed for astronomy can be used to address key challenges in atmospheric science (Fig. 1). Stafford Withington, Emma Turner and Michael Simmons from the Cavendish laboratory, together with David Newnham and Anna Jones from BAS, and Peter Wadhams and Robin Clancy from DAMTP, brought together 45 delegates from the UK's atmospheric science and astronomy communities with strong interests in this region of the spectrum.

Amongst the 12 presentations were keynote talks from **John Pyle** (University of Cambridge, Chemistry), who described current challenges in observing and modelling the stratosphere, while long-time leader in the field **John Harries** (Imperial College, London) reviewed the history and recent developments in far-infrared atmospheric spectroscopy. Atmospheric absorption in the submillimetre-wave range

is dominated by rotational transitions of water vapour, but it is not just the resonant lines that play a part. Broadband absorption has been observed for decades, and yet the functional form, and indeed the mechanism behind this 'continuum' component is still poorly understood. Real-time, low spectral-resolution observations of the whole of the submillimetre-wave spectrum would make an important contribution towards understanding the atmosphere's dynamic energy balance. **Jonathan Murray** (Imperial College London) presented his work with the Tropospheric Airborne Fourier Transform Spectrometer (TAFTS), which has flown on various research aircraft and measured far infrared emission at frequencies above 2.5 THz. TAFTS has been used to constrain the water vapour continuum in far-infrared radiative transfer models, but the continuum in the submillimetre region has not been similarly validated with in situ measurements despite its large contribution (Fig. 2).

Several speakers focused on observing cirrus clouds, which have spectral signatures in the submillimetre-wave range. This is a pivotal topic as clouds exert a large influence on the Earth's climate, and ice clouds in particular absorb radiation at long wavelengths, which retains heat in the lower atmosphere. There is a need for more and better observations to deduce the distribution of complex ice habits (shapes) that exist in their natural environment.

**Stuart Fox** of the Met Office described the International Sub-Millimetre Airborne Radiometer (ISMAR), which has five channels working in the 183 to 664 GHz range. At the time of the workshop, ISMAR was preparing for its maiden test flight from Prestwick. **Chris Westbrook** from the University of Reading gave an overview of the development of an innovative ground-based cloud radar, which will measure multiple frequencies above 100 GHz, revealing finer details of small atmospheric particles.

Many important chemical species have spectral lines in the submillimetre-wave and THz regions. John Pyle explained that the processes of seasonal polar stratospheric ozone depletion should now be regarded as a 'solved problem', and that the new challenge is to maintain a global network of observing stations to monitor ozone recovery

and other gases such as carbon dioxide, nitrogen dioxide and methane, which affect the climate and the ozone layer.

**Peter Wadhams** gave a fascinating, if somewhat disturbing, review of methane emission from the Arctic shelves, which might increase catastrophically because of permafrost melt releasing plumes from methane hydrates (Fig. 3). Other ozone depleting gases such as chlorinated and brominated species, for example HOBr, have been seen to increase significantly in the Polar Regions in recent years (Fig. 4), but there are large uncertainties regarding their sources and sinks. The study of chlorinated and brominated gases, which have complex submillimetre-wave spectra, was discussed by the audience as being one of the major challenges where advanced astronomical instrumentation could play a role. Higher up, in the mesosphere, chemicals such as nitric oxide are observed to correlate with the timings of geomagnetic storms, as shown by **David Newnham**, with results from the BAS's millimetre-wave radiometer deployed at Halley in Antarctica, which measures line emission at 230 GHz and 250 GHz using SIS mixers.

**Hugh Pumphrey** (University of Edinburgh) spoke about the Microwave Limb Sounder (MLS) on the Aura satellite, its measurements

of carbon monoxide and sulphur dioxide, and a planned successor, the Scanning Microwave Limb Sounder (SMLS). He also presented work on behalf of **Daniel Gerber** (RAL) who is using quantum cascade lasers as the local oscillator in a future heterodyne satellite instrument, the Low-Cost Upper atmosphere Sounder (LOCUS), to detect chemicals such as atomic oxygen and hydroxyl radicals which are indicators for the energy balance in high atmospheric layers. Nearer to home, **Rod Jones** (University of Cambridge, Chemistry) spoke about his work with small, low cost electrochemical sensors for molecules such as NO, NO<sub>2</sub> and CO deployed on lamp posts and bicycles in Cambridge to measure air quality. **Nick Walker** (University of Newcastle) presented work on Fourier Transform Microwave Spectrometers, which have been used to measure the free induction decay of a gas following the application of a microwave pulse.

The SPECTRO-ICE Workshop was a great success, and many delegates expressed a desire to have future meetings covering the same general themes. The Workshop forged links between communities that have not traditionally worked together, despite their common interest in submillimetre-wave spectroscopy and radiometry ■

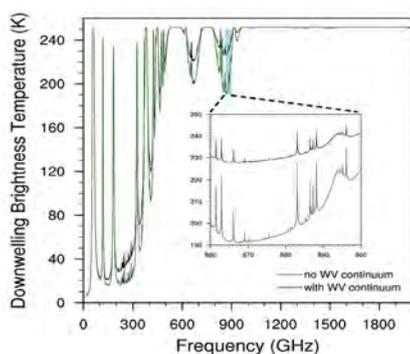


FIG 2.

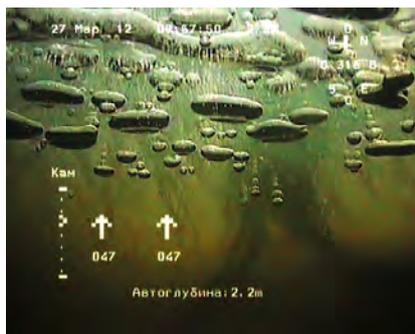


FIG 3.

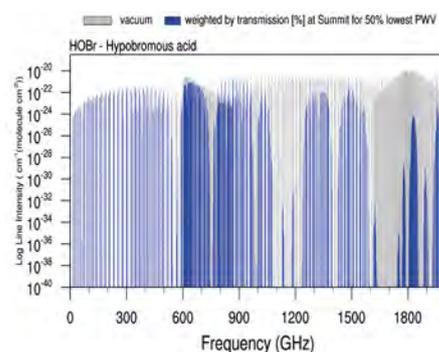


FIG 4.

**FIG. 1.** The SPECTRO-ICE Workshop at the Møller Centre.

**FIG. 2.** Brightness temperature spectrum at submillimetre wavelengths simulated by the Atmospheric Radiative Transfer Simulator (ARTS) for zenith observing at Summit, Greenland (3210 metres above sea level). The black line includes both line and continuum absorption whereas the green line shows only line absorption.

**FIG. 3.** Methane bubbles rising in the East Siberian Sea, flattening themselves against overhead sea ice. Photograph taken using an underwater vehicle. Courtesy of Natalia Shakhova.

**FIG. 4.** Intensities of submillimetre line transitions for Hypobromous Acid (HOBr). Grey lines are those measured in a vacuum and blue lines are weighted by the atmospheric transmission at those frequencies. Taken from the HITRAN 2012 database.

# Unravelling the Chain Fountain

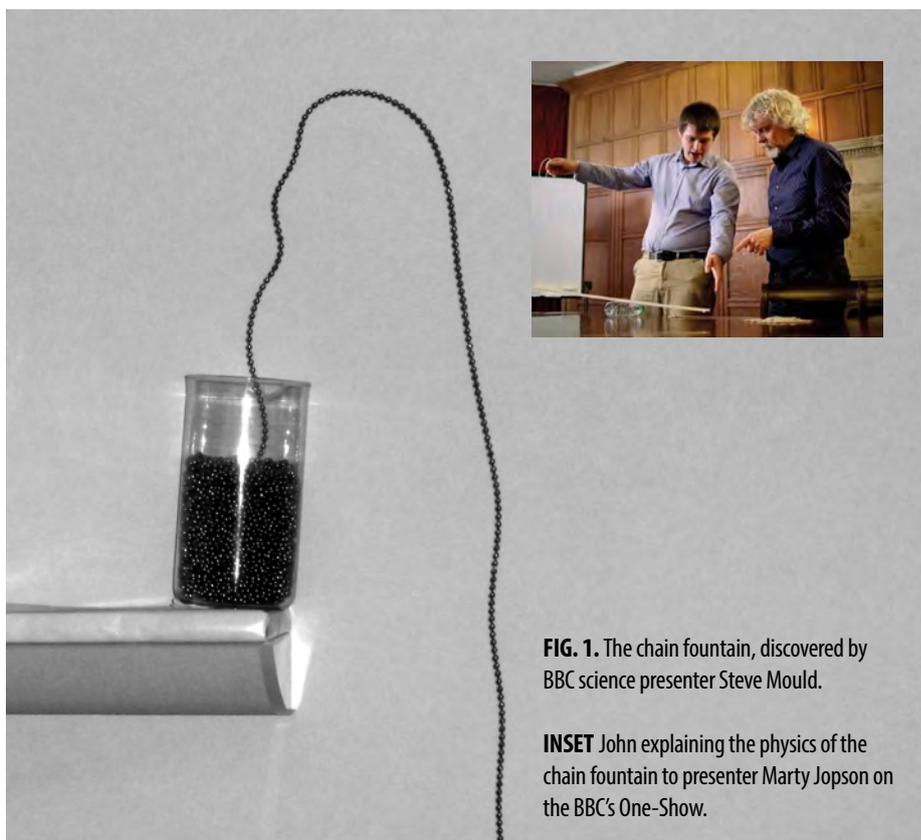


**JOHN BIGGINS**, recently appointed as an Early Career Lecturer in the Laboratory, explains the amazing chain fountain effect.

Imagine you put a long chain in a pot, hold it above your head, pull one end out and release it. What happens next? This may sound like a school physics problem, but when BBC science presenter Steve Mould tried this, he got a surprise: the chain not only spontaneously flowed down to a pile on the floor, it also leapt up in an arc above the pot (Fig. 1). Steve made a mesmerising slow-motion video of his 'chain fountain', and millions of people watched it on YouTube, but no-one could explain why the chain arced up before flowing down to the ground.

Amongst the viewers were Mark Warner and the present author, who thought the leaping chain would make a wonderful mechanics problem for the Cavendish's schools outreach website, [www.isaacphysics.org](http://www.isaacphysics.org) - they just needed to understand it first. As what was originally thought to be an afternoon's work overran into a week, and then a month, they realised the leaping could not be explained within the classical theory of chains - this was not a school problem, it was a research problem.

The chain clearly flows to the ground because gravity pulls it down. The tough question is, if gravity pulls down, why does the chain leap up? We realised that the leap must be caused by the pot pushing up on the departing chain, but how can a pot push? We imagined a chain made of freely jointed rigid rods, and reasoned that when the next rod in the chain is pulled into motion, it is pulled upwards at its end by the preceding rod. Just like a seesaw,



**FIG. 1.** The chain fountain, discovered by BBC science presenter Steve Mould.

**INSET** John explaining the physics of the chain fountain to presenter Marty Jopson on the BBC's One-Show.

when the rod is pulled upwards at one end, it starts to rotate and the other end moves down. It then bounces off the pot, receiving the upwards push that causes it to leap into the air.

After publication, our explanation took on a life of its own. It was covered everywhere from the *Daily Mail* to the *New York Times*, offered on national TV by Stephen Fry during *QI*'s Christmas special, and inspired a three-story chain-fountain sculpture in Guatemala. Most recently I explained the fountain on BBC1's the *One-Show* (Inset, Fig. 1), while Steve demonstrated a chain

fountain leaping a record breaking 1.5 m above his head by standing on a crane. Best of all, the explanation is sufficiently simple that, in an unusual synergy of research and teaching, the Isaac-physics team now regularly demonstrate the chain fountain in schools, and budding physicists can fully understand the mechanics of what is going on by working through a problem set at [www.isaacphysics.org/questions/chain\\_fountain](http://www.isaacphysics.org/questions/chain_fountain) ■

The BBC video is at [www.bbc.co.uk/programmes/p02tcq19](http://www.bbc.co.uk/programmes/p02tcq19)



## Administering the Laboratory

There have been a number of recent arrivals and departures from the Administration Section of the Laboratory, including the new Department Administrator **GILLIAN WEALE** who reflects on the challenges.

It has been a great pleasure to get to know my colleagues in the Department's administration, and all its support areas, since joining the Cavendish Laboratory from the Faculty of English in January this year. Coming from the Arts and Humanities, where the chief research support for academics is provided through libraries, it has been striking to see the much greater variety of support needed for research in a large science department, from cryogenics to knowledge transfer, computing to electronics, and catering to radio telescopes. The need therefore to maintain an effective and enabling administrative and technical operation is vital, and my primary responsibility is to ensure that all parts of the support structure make a

meaningful contribution to the academic mission of the Department. With this end in view, we are this summer undertaking a review of core administrative processes and procedures, seeking to streamline where we can, and taking advantage of IT systems and different ways of working.

We are enormously lucky to have a dedicated and capable cadre of staff in the administrative and accounts team (pictured), and we will be augmenting this during the autumn with three new positions to support finance, human resources and graduate student administration. The establishment of the Maxwell Centre, and the Cavendish III project present further challenges for the Department's administration, as we

look to contribute to these significant developments at the same time as making improvements in the way we do 'business as usual'. For me personally, this is the professional challenge of my career to date, but the kindly support I have received from academic and administrative colleagues has been both a comfort and an inspiration, to which I shall endeavour to do justice ■

**IMAGE, ABOVE.** Members of the Administration Section on the occasion of the retirement celebrations for Stephen Ruffles. Front row (left to right): Debbie Hall, Jon Slater, Gillian Weale, Stephen Ruffles, Emily Challis, Robert Hay, Clare Dickinson. Back row (left to right): Petra Beranova, David Cramp, Tina Laphorne, Alison Dann, Jo de Bono, Andrew Snushall.

## The Cavendish Research Staff Committee Continuing an Old Tradition

**ADRIAN IONESCU** and **CHRIS BRAITHWAITE** (Chair of the RSC) describe the efforts being made to support post-doctoral researchers during key stages in their careers.

In 1893, Thomson introduced the fortnightly meetings of the **Cavendish Physical Society (CPS)** at which all the staff and students, as well as the increasing numbers of visitors, got together to discuss their research, recent developments in other laboratories and all other items of topical scientific interest. These occasions were enhanced in 1895 when Mrs. Thomson provided tea for all the participants and this tradition continues today with the receptions after the CPS lectures.

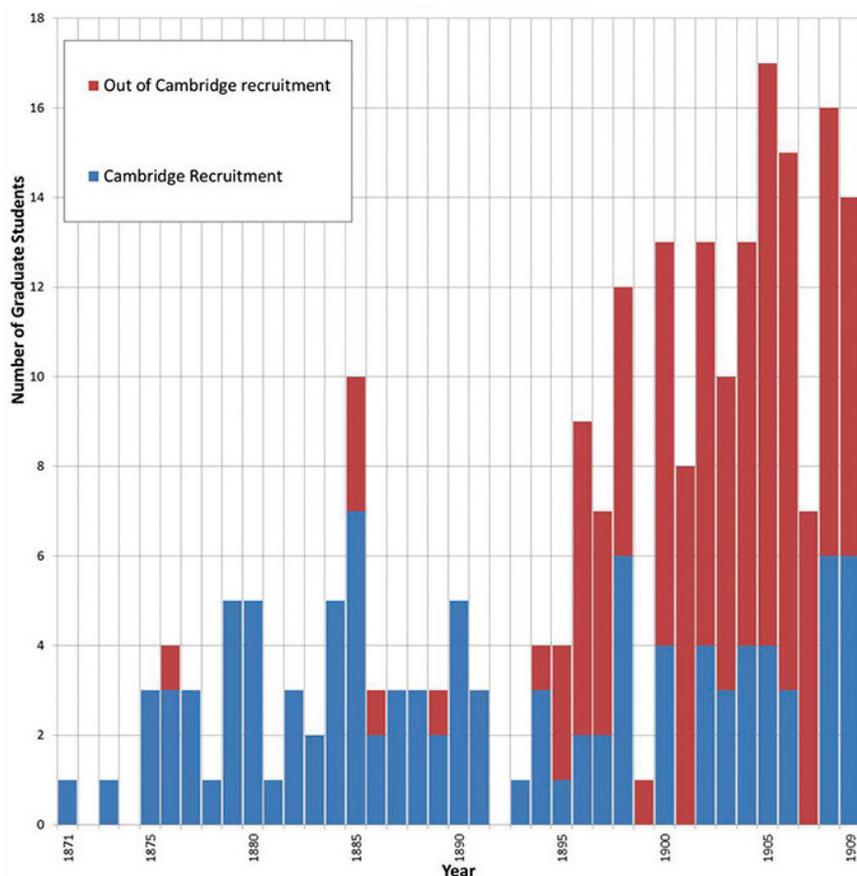
But the numbers were small and manageable in those days. Figure 1 shows that in 1895 there were typically only about 4 new graduate students per year (data from Isobel Falconer). The great increase in student numbers from 1895 onward was partly due to the change of regulations which allowed students from other universities to study for a research degree in Cambridge. These figures can be compared with the present numbers of about 80-90 new graduate students per year and a total cohort of over 300. In addition, there are

typically 150-200 post-doctoral researchers who are the power-house behind the research activity and crucial to the success of the Laboratory.

The key roles of morning coffee and afternoon tea remain an essential component of the programme of daily events in the Laboratory and were crucial in Watson and Crick's discovery of the double helix and John Clarke's invention of the SLUG (Superconducting Low-inductance Undulatory Galvanometer). These tend to be centred on the research groups nowadays because of the enormous scale of the Laboratory.

But there is more to it than just communicating about science – the culture has to be one of co-operation and friendly interaction across the Laboratory. These chance encounters have the potential to develop new collaborations, as well as friendships. So, how can one entertain and socialise today with nearly a thousand people involved in the activity of the Laboratory? This is one of the tasks of the **Cavendish Research Staff Committee (RSC)**.

The RSC came into being in 2010 on the initiative of the Laboratory as a means of giving some level of voice to the post-doctoral researchers (PDRs) and other researchers on short-term contracts within the department. All research groups are represented on the Committee. The need was highlighted during our successful efforts to win Athena Swan Gold Award status for the Laboratory. Besides requiring action on gender-equality issues, the process also examined efforts that have been made to



**FIG.1.** Recruitment of graduate students to the Cavendish Laboratory from Cambridge and Elsewhere

accommodate staff on short-term contracts. In 2014 the University further emphasised the importance of this group of employees for research and teaching by opening the Office of Post-doctoral Affairs, partly inspired by the success of the Postdocs of Cambridge Society. The latter was established *ad hoc* by PDRs from various departments of the University a few years earlier in order to have a collective voice on issues of concern such as career development, contract research conditions, College affiliation, social and sporting issues and so on.

Since 2010 the Cavendish RSC has aimed to give research staff a representative role in the management of the Department and in turn has organised events to promote the well-being of PDRs. It has organised welcome events in October every year for new arrivals, a number of successful career-building workshops, for example for fellowship applications, and several social gatherings, such as the research staff teas. In 2014 we were invited to contribute more formally to the management of the Department through participation in the Personnel Committee.

At the last October event, entitled 'Have your say', five areas of interest for the research staff community were discussed and problems highlighted. The topics were Professional and Personal Development, Teaching, Research, Mentorships and Social activities. The committee has engaged with the Teaching Committee to give research staff written accreditation for their co-supervision of Part 2 and 3 projects. We have also recently organised two Beer & Pizza Happy Hour events (Fig. 2), at which researchers, PhD students and assistant staff in the Cavendish meet in a social setting, promoting interaction and networking between members of the Laboratory.

We have arranged for some of the University-run courses related to professional and personal development to be given at the West Cambridge site, rather than in the city centre, to facilitate attendance. A further major project will be the organisation of the Research Day in June 2016 to which members from all groups will be invited to provide talks and posters about their research to foster greater co-operation and collaboration within the Laboratory.

We realise that over the years the milieu may have changed from tea and cake to beer and pizza, but they stem from the same basic need - to facilitate ground-breaking research in a creative and co-operative environment.

We are always interested in hearing from alumni, businesses and industry if they would wish to participate in, or sponsor our events. If you have any suggestions related to our activities, please contact: Adrian Ionescu ([ai222@cam.ac.uk](mailto:ai222@cam.ac.uk)), Secretary of the Research Staff Committee ■

### Programme of events

#### Thursday 10 September 2015

4-6 pm, Pippard Foyer, Research Staff Happy Hour.

#### Wednesday 23 September 2015

3.30 pm Cavendish Common Room, Research Staff Tea-time: Chris Summerfield, Head of the Cavendish Mechanical Workshop. *How to make the best use of the mechanical workshop.*

#### Thursday 15 October 2015

4-6 pm, Small Lecture Theatre and Foyer, Research Staff October Event: Careers Services, Cambridge Enterprise, and others. *Career Development*

#### Wednesday 21 October 2015

3.30 pm Cavendish Common Room, Research Staff Tea-time: Sarah E. Bohndiek. *Academic Mentorship at the Cavendish.*

#### Wednesday 11 November 2015

3.30 pm Cavendish Common Room, Research Staff Tea-time: Lisa Jardine-Wright. *How to get Research Staff involved into Outreach Activities.*

#### Wednesday 9 December 2015

3.30 pm Cavendish Common Room, Research Staff Tea-time: Malcolm Longair. *Reflections on Career Progression.*

#### Wednesday 20 January 2016

3.30 pm Cavendish Common Room, Research Staff Tea-time: Gillian M. Davis. *How to make money out of your research.*



FIG. 2: Research Staff and colleagues enjoying themselves at the first Cavendish Happy Hour

# Quantum Mechanics for Everyone

During visits to the Laboratory by interested members of the public, and indeed during a recent visit of HRH The Duke of York KG, our lavish use of quantum ideas and terminology often require further explanation. This essay is your editor's attempt to explain in simple terms why intuitive ideas about the way the world works break down on the microscopic scale.

Quantum mechanics is the most successful physical theory we possess. It describes with astonishing precision the way in which matter works at the atomic and subatomic level. Some features of quantum mechanics have no counterpart in classical physics and are **distinctly non-intuitive** from a classical perspective. But these features of the theory can all be traced to phenomena which have been securely established by laboratory experiment.

Let us first contrast how matter behaves in the classical and quantum regimes. In classical physics, we deny that there is internal structure to matter. It can be infinitely divided up and the laws of physics remain the same however finely we carve it up. But this is not the case in quantum physics. At the atomic level, we can no longer keep dividing matter up into arbitrarily finer and finer pieces. For example, there are only certain allowed energies which the electrons can take up in atoms – we say that the energy levels in the hydrogen atom, for example, are **quantised** rather than continuous. This is an entirely quantum mechanical effect with no counterpart in classical physics.

In classical physics, waves and particles have quite separate existences. Radio waves, water waves and sound are, for example, described very precisely by the equations of classical physics. But in quantum physics, there is not the same distinction between waves and particles. **Waves can behave like particles and particles can behave like waves.** The simplest example is the physics of light.

One of James Clerk Maxwell's great discoveries was that light consists of the oscillations of electric and magnetic fields – electromagnetic waves. But 40 years later, Einstein predicted that light has particle properties and 10 years after that Millikan demonstrated this by experiment. Just over a decade later, it was shown by Clinton Davisson and Lester Germer in the USA and by George Thomson, son of J.J. Thomson, that electrons can behave like waves. As the famous aphorism has it:

*'(J.J.) Thomson the father showed that the electron is a particle and (G.P.) Thomson the son showed that it is a wave.'*

Thus, a description is needed which can endow matter with both wave and particle properties at the atomic level.

Another non-classical property of matter at the atomic level is that of **spin**. This is an intrinsic property of, for example, the electron and it combines with the rotational motion of the electron in an atom **as if** it were a genuine rotation of the electron about its axis. But this is an incorrect way of thinking about spin in quantum mechanics – if it did rotate about its axis, its surface would rotate about 60 times the speed of light, which is not allowed. Rather spin is a purely quantum property of particles and it can be combined with the particle's orbital motion **as if** it were a rotating particle.

The common thread linking all these non-classical quantum phenomena is the presence of **Planck's constant  $h$**  in the expressions for processes at the quantum level. Whenever you see  $h$  appearing in an equation, this immediately means quantum rather than classical physics is involved.

Thus,

- the quanta of light and electromagnetic radiation have energy  $h\nu$ , where  $\nu$  is the frequency of the wave.
- the wavelength  $\lambda$  of the waves associated with an electron is related to its momentum  $p$  by the relation  $\lambda = h/p$
- the intrinsic spin of the electron is  $h/4\pi$  when projected onto any axis.
- an electron in the lowest energy state of the hydrogen atom has energy  $-me^4/8\epsilon_0^2h^2$ , where  $m$  and  $e$  are the mass and charge of the electron and  $\epsilon_0$  is a constant, the permittivity of free space.

A theory was needed which tied together all these various aspects of physics on the scale of atoms in a self-consistent manner. This was the great problem solved by Heisenberg, Schrodinger, Dirac, Born, Pauli and their colleagues in the 1920s. Before their great discoveries, quantum phenomena had been described simply by bolting quantum concepts onto classical physics. But as described by Max Jammer, this resulted in

*'a lamentable hodgepodge of hypotheses, principles, theorems and computational recipes rather than a logical consistent theory.'*

The revolutionary break-through was made by the 23-year old Werner Heisenberg in 1925 when he had the idea that what had gone wrong with classical physics was that the wrong rules of kinematics, meaning the description of motion, were being used. Heisenberg argued that quantum concepts

should be applied, not only to quantities such as the frequencies of oscillators, but also to the **kinematics** of the electron itself. His profound insight was that the spatial position of the electron should be subject to quantum rules, just as in the case of its momentum. The classical kinematics of Galileo and Newton had to be replaced by their quantum theoretical counterparts.

Within a few days of analysing Heisenberg's results and sending the paper off for publication, Max Born realised that Heisenberg's quantum conditions had to be applied to the positions  $x$  and momentum  $p$  of an electron according to the rule:  $px - xp = h/2\pi$ . In ordinary algebra  $px - xp = 0$ , for example  $4 \times 3 = 3 \times 4$  and so  $4 \times 3 - 3 \times 4 = 0$  and the numbers 4 and 3 are said to commute. What had gone wrong is that the wrong type of algebra was being used. What was needed was a form of algebra in which quantities such as  $p$  and  $x$  are **non-commuting** and that algebra turned out to be the algebra of matrices and operators, in which **non-commuting variables** appear naturally. Heisenberg was very worried about this step in his analysis, but it turned out to be crucial in the development of the theory.

The elaboration of the theory by the great pioneers of quantum mechanics resulted in

a number of highly non-intuitive features, but these have all now been confirmed by precise experiments. For example, for pairs of non-commuting variables such as position and momentum, these can only be measured to a precision given by **Heisenberg's Uncertainty Principle**. This states that the product of the uncertainties in position and momentum,  $\Delta x$  and  $\Delta p$  respectively, cannot be less than  $h/2$ ,  $\Delta x \Delta p > h/2$ . But these are not the ordinary types of probabilities found in courses on statistics. At no point are probabilistic concepts introduced into the postulates of quantum mechanics, but the variables turn out to be determined with precisely defined probabilities by the fundamental constants of physics.

Another consequence of this non-commutativity is that there are inevitably fluctuations in the occupancy of quantum states – these are called **zero-point fluctuations** and their impact upon observable phenomena has been demonstrated in numerous laboratory experiments. These are the sorts of quantum fluctuations which are believed to have given rise to primordial structures in the Universe.

Another non-intuitive feature of quantum mechanics at the fundamental level is that

phenomena which might have happened, but didn't, can affect the outcome of an experiment – this property is quite inconsistent with classical logic. This comes about because of the way in which the probabilities are determined at a fundamental level before the measurement is actually made. Variants of this feature of quantum mechanics find applications in quantum security keys.

The theory of quantum mechanics is at the heart of all solid-state electronic devices, making use of features such as quantum tunnelling, for example, in microelectronic circuits. These aspects of our world may seem non-intuitive, but that is how the world works at the quantum level. Understanding and exploiting these phenomena are among the greatest scientific challenges facing experimental and theoretical physicists. The contemporary digital society is wholly dependent upon the fruits of these discoveries and it is certain that there are many more surprises in store ■

#### MALCOLM LONGAIR

For more technical details about how quantum mechanics came about, the reader may wish to dip into my recent book *Quantum Concepts in Physics: An Alternative Approach to the Understanding of Quantum Mechanics*, (2013). Cambridge: Cambridge University Press.



**Fig 1.** During a visit to the Laboratory in November 2014, Hannah Stern explains to The Duke of York the apparatus used to understand the physics of the semiconducting polymers which are used in polymer solar cells. Neil Greenham, Head of the Optoelectronics Group, is on the left. (Photograph by Phil Mynott Photography).



**Fig 2.** During a more recent visit to the Kavli Institute for Cosmology in July 2015, The Duke of York was shown the high technology developments being carried out in the Battcock Centre for Experimental Astrophysics for the Square Kilometre Array (SKA). Nima Razavi explains the prototype antenna, one of many hundreds of thousands of such antennae which will be needed to observe the sky with extreme sensitivity at low radio frequencies. (Photography by Kelvin Fagan).

## Sir Sam Edwards

### 1928–2015



**It is with great sadness that we report the death of Professor Sir Sam Edwards, Cavendish Professor Emeritus of Physics and a Fellow of Gonville and Caius College. He died on 7 May 2015, aged 87.**

Sam was born and brought up in Swansea and his Welsh roots were very important to him. A grammar school boy, he won a scholarship to Cambridge to study mathematics at Gonville and Caius College. His PhD studies were carried out under Julian Schwinger at Harvard University on the structure of the electron, which involved using advanced techniques of quantum field theory. Seeking challenges outside particle physics, he realised that he could apply the techniques of quantum field theory to complex problems in condensed matter physics. His seminal paper entitled *A new method for the evaluation of electric conductivity in metals* opened up a vast field of research in the quantum mechanics of electrons in random potentials. As David Khmel'nitskii has written,

'Sam Edwards, then at Birmingham, was introduced to the problem by Peierls and made the decisive step by considering the transport of electrons elastically scattered by a random potential. This step had dual

importance: first of all, Edwards came up with a field theory, which corresponded to averaging over random potentials; secondly, he developed a very effective diagrammatic technique, which allowed him to calculate the Drude conductivity and gave to those who came after him an efficient tool for further research'

In subsequent years prior to his arrival in Cambridge, he published innovative papers on *The statistical dynamics of homogeneous turbulence* (1964), *The statistical mechanics of polymers with excluded volume* (1965), *The theory of polymer solutions at intermediate concentration* (1966) and *Statistical mechanics with topological constraints* (1968).

The theoretical activity in the Cavendish received an enormous boost in 1972 with his appointment as John Humphrey Plummer Professor of Physics. He brought quite new dimensions and directions to both the theoretical and experimental work of the Laboratory. As stated in the book *Stealing the Gold: A Celebration of the Pioneering Physics of Sam Edwards* (2004),

'Over the course of nearly half a century, Sam Edwards has led the field of condensed matter physics into new directions, ranging from the electronic and statistical properties of disordered materials to the mechanical properties of granular materials. Along the way, he has provided seminal contributions to fluid mechanics, polymer science, surface science and statistical mechanics.'

Among his major contributions was the expansion of the range of theoretical and experimental work in polymer science and statistical physics. The Solid State Physics Group was renamed the Theory

of Condensed Matter (TCM) Group, thus incorporating polymer and complex fluids into its interests.

Almost immediately, however, on 1 October 1973, Sam became Chairman of the Science Research Council, a position he was to hold for four years. Nonetheless, he continued to supervise his graduate students throughout this period, which saw some of his most original contributions to Condensed Matter Theory. Of particular importance was the *theory of spin glasses* which he developed with Anderson in 1975. He employed the technique known as the *replica trick*, which he had already used in his study of polymers, to work out the ground state and properties of spin glasses. As Heine expresses it, 'A whole industry on spin glasses and then neural networks developed.'

Edwards' second major contribution during this period was the theory of the dynamics of polymers, the process known as *reptation*, with Masao Doi.

Entangled long chain molecules wiggle as if they were confined to a tube, the motion consisting of extending out one end of the tube and retracting at the other (see Box, page 19). The dynamics of reptation described by their theory proved to be very successful and now underpins the huge, industrially important field of rheology. The summation of their pioneering work was published in their influential book *The Theory of Polymer Dynamics* (1986).

What is remarkable is that Sam made these fundamental contributions to theoretical physics, while carrying out his responsibilities as chairman of the Science Research Council in London. He would supervise research students on the train and worked out multi-

dimensional integrals during meetings, filling up successive 'little red books'.

During his early years in the Cavendish he brought new theoretical initiatives to the TCM group which were to prove to be major growth areas. In particular, he realised the need to make full use of his industrial connections to support theoretical physics activities. The Industrial CASE award scheme provided opportunities for some outstanding graduates, including Robin Ball, Mark Warner and Michael Cates. Other graduate students included Richard Needs and Tom McLeish.

Sam was appointed Cavendish Professor in 1984 in succession to Brian Pippard and took on the role of Head of Department for the next five years. He had by then acquired vast experience of national and international science politics. He had served as a member of the Council of the European Physical Society from 1969-71. He had been a member of various committees of the Science Research Council since 1968 and of the Council's Science Board since 1970. In 1971 he was appointed a member of the University Grants Committee. He was Chairman of the Defence Scientific Council from 1977-80 and Chief Scientific Adviser to the Department of Energy from 1983 to 1988. He had also served as Vice-President of the Royal Society, of the Institute of Physics and had been the President of the Institute of Mathematics. Thus, he had a very wide range of contacts in government and industry and used that experience to begin a major expansion of the scope of the Laboratory's activities.

He was to exploit his industrial contacts with remarkable effect. He was famous for hosting dinners for senior figures in industry and government in Caius College, where he had accumulated a superb, and large, wine

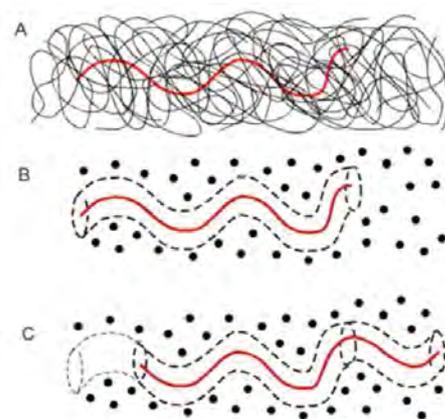
collection. When I took over as the Head of the Cavendish in 1997, his only advice to me was 'Have dinners!'

Sam realised that the Government and the Research Councils could not be relied upon to provide the resources for new activities. Rather, the way to do new things was to become much more closely associated with the needs of industry and to enhance the support they could provide to the research programme. This was also attractive to Government who were keen to promote research which would be of benefit to industry. During Sam's five-year period as Head of Department new groups were created in Microelectronics led by Haroon Ahmed (1983), Semiconductor Physics by Michael Pepper (1984), Optoelectronics by Richard Friend (1987), Polymers and Colloids by Athene Donald (1987) and the Interdisciplinary Centre for High Temperature Superconductivity, a collaborative effort between a number of departments (1987) - all of these new activities were to have strong industrial connections.

Sam's contributions to the Cavendish and to physics in general were immense. And through it all he remained affable, approachable and a friend to all his colleagues and students. I remember vividly his love of opera where we often bumped into him and his wife. I especially remember his great affection for Janacek's *Cunning Little Vixen*, one of the most touching and humane operas in the repertory.

Sam will be greatly missed. Our thoughts are with his wife Merriell and their family ■

**MALCOLM LONGAIR**



#### DOI AND EDWARDS ON REPTATION

Reptation is the thermal motion of very long linear, entangled macromolecules in polymer melts or concentrated polymer solutions. The word is derived from the word reptile, suggesting the movement of entangled polymer chains as being analogous to snakes slithering passed one another. The concept was introduced by Pierre-Gilles de Gennes in 1971 to explain the dependence of the mobility of a macromolecule on its length. Edwards and Doi later refined reptation theory in a number of articles in 1978-79 and subsequently in their classic book on the subject in 1986, *The Theory of Polymer Dynamics*.

The sketches illustrate the process of reptation for entangled polymers.

- An illustration of an entangled polymer solution, the polymer of interest being shown in red.
- The 'tube' surrounding the polymer formed by the surrounding polymers which restricts motion in directions transverse to the outline of the polymer.
- As the polymer reptates out of its original 'tube', a new tube is formed as the old one disappears.

Diagrams and text courtesy of Rae Anderson, University of San Diego.

# Derek Vonberg

## 1922–2015



**We are sad to report the death of Derek Vonberg at the age of 93 in April 2015. He was one of the UK pioneers of radio astronomy from the heroic immediate post-War years when the discipline scarcely existed.**

In 1945, immediately after the War, Martin Ryle and Vonberg joined the Cavendish Laboratory Radio Group under Jack Ratcliffe. Ryle came from five years of development of radar at the Telecommunications Research Establishment. Vonberg was an electrical engineer newly arrived from Imperial College.

Their first project was to measure the properties of the radio emission from the Sun. There was scarcely any money for equipment, but they were able to buy considerable amounts of surplus War electronics very cheaply and also acquire large amounts of high quality German radar equipment which had been requisitioned after the War. They took away five truckloads of surplus equipment from the Royal Aircraft Establishment (RAE) at Farnborough, including two 7.5m Wurzburg antennae, several 3m dishes and a vast amount of high quality German coaxial cable – they were all superior to the UK equipment and were to be used for many years (see CavMag13).

A large sunspot group occurred between 20 July and 1 August, 1946. The angular resolving power of the radio antennae was not sufficient to resolve the disk of the Sun. Ryle and Vonberg therefore developed new receiver techniques to create a radio interferometer, the antennae being separated by several hundred metres in order to provide high enough angular resolution. Only later was it realised that they had invented the radio equivalent of the Michelson interferometer. Their observations showed conclusively that the radio emission originated from a region on the surface of the Sun similar in size to that of the sunspot region.

These measurements of the active sun showed that the brightness temperature of the radiation was  $2 \times 10^9$  K, too high to be explained by any thermal process - they concluded that the emission process must be non-thermal. They then undertook further experiments on the active sun and demonstrated that the emission was strongly circularly polarised, showing conclusively that the emission was indeed non-thermal. This was all reported in one short *Nature* paper in 1946. The paper is a wonderful example of clarity and brevity - it is only one

page in length. Vonberg reminisced in 1971 about his time working with Ryle:

‘Ryle really was brilliant at thinking of ways of getting enormous amounts of information with a couple of old bedsteads and some bits of copper tube ... He was absolutely first-class. He was quite brilliant and scientifically uncompromising but very, very approachable. It was quite difficult to keep one’s end up in that he was so good and so clever that very few things which the ordinary mortal produced really contributed a great deal.’

Vonberg left the group after 3 years and became the leader of the efforts at the Hammersmith Hospital to develop the cyclotron, producing neutrons and short-lived radioactive isotopes for medical purposes. He became a very distinguished medical research scientist, leading the Cyclotron Group at the hospital, for which he was awarded the CBE. A very happy celebration of his life and work was held in the Kavli Institute on 20 June 2015 organised by his son, David Vonberg with the assistance of the Cavendish Astrophysics Group ■

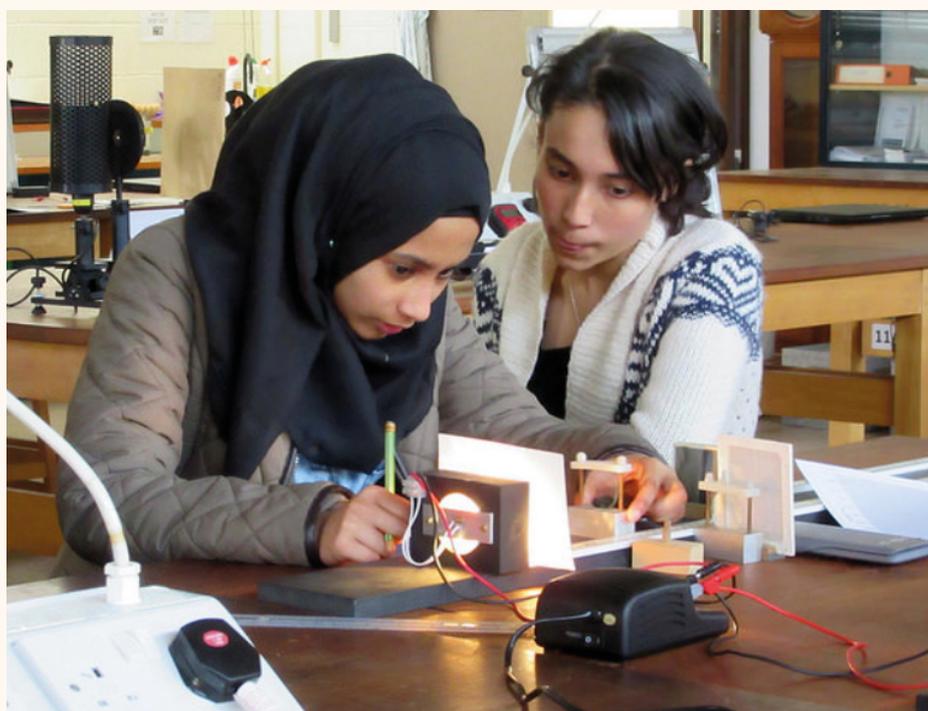


The rifle range hut and antennae in 1948. The ‘bedsteads’ behind the foreground antennae were used by Ryle and Vonberg in their observations of sun-spots. At the largest antenna separations, the antennae encroached into the University Rugby ground. The house where Ryle and Vonberg lived as research students at 5A Herchel Road is just behind the antennae.

# Cambridge Colleges Physics Experience, Work Experience, Physics at Work and Isaac Physics



**JACOB BUTLER** and **LISA JARDINE-WRIGHT** bring these activities up to date.



## Cambridge Colleges Physics Experience

This year's Cambridge Colleges Physics Experience (CCPE) events have recently come to a close. They have been well attended this year, tripling in size since their inception three years ago. Over 1200 students from 126 schools across the country attended, and over a hundred more have visited through college-run events during the Easter and Summer breaks. Preliminary responses to the student and teacher questionnaires have been very positive, following the trend of previous years. Steven Martin is currently compiling these data and a three-year report will be released

shortly. Using data from the admissions office, this report will include an analysis of how effective the programme has been in encouraging students to study at Cambridge.

A meeting with each college's Student Liaison Officer (SLO) will be held in September to arrange the next year's timetable and to formalise the hosting of summer school events.

If you are interested in next year's events, details will be found at <http://outreach.phy.cam.ac.uk/programme/CCPE>

## Work Experience

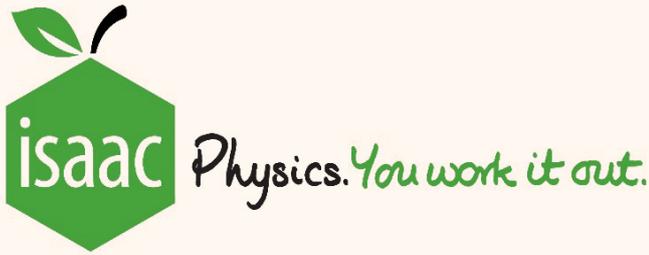
The annual work experience programme placements have begun. From a particularly large number of applications, there will be 20 students attending placements with seven of the Cavendish research groups over the next two months. So far these students have prepared a simplified guide and quiz for use in the Cavendish museum, and helped with the development of the Isaac Physics website.

Contact details: details of the application process can be found at <http://outreach.phy.cam.ac.uk/wex>

## Physics at Work

School bookings for September's Physics at Work exhibition have recently closed. This year around 2200 school pupils from across the country will attend talks given by Cavendish research groups and scientists from a variety of commercial and industrial fields. There will be 20 exhibitors this year and the event will run from 22nd-23rd September. Bookings for the 2016 will be available in May 2016.

<http://outreach.phy.cam.ac.uk/programme/physicsatwork>



## Teachers have Isaac Physics mark homework for them!

Our new teacher features on Isaac Physics allow teachers to select and set questions from Isaac for homework and instantly receive the marks for each of their students. Teachers have been delighted with this facility. Sample quote from twitter: "Love @isaacphysics #assignments! Tasks auto-marked 12h before deadline!" Below is an example of the live mark sheet presented to teachers – it updates in real time so that teachers can see the instant progress of the students if they are using Isaac during a lesson.

The screenshot shows the Isaac Physics interface for a teacher named Lisa. It displays the 'Assignment Progress' for 'Board 1' (Physics Masterclass 2015 - Board 1). A summary bar indicates that 24 out of 89 students have completed the board correctly. Below this is a table for the question 'Shelf and Brackets'.

Question: Shelf and Brackets	79%	73%	53%	36%	
Meryem	✓	✓	✓	✓	4 / 4
Shiza	✓	✓	✓	✓	4 / 4
Oliver	✓	✗	⊙		1 / 4
James	✓	✓	⊙	✓	3 / 4
Nathan	✓		⊙		0 / 4
Lewis	✓	✓	✓		3 / 4
Fiona	✓	✓	✗	✓	3 / 4
Matthew	✓				1 / 4
Roman	✓		⊙		1 / 4
Amy	✓	✓	⊙	✗	2 / 4
Cole	✓	✓	✓		3 / 4
Michael	✓	✓	✓	✓	4 / 4
Eleanor	✓	✓	✓	✓	4 / 4
Cormac	✓	✓	✓	✓	4 / 4

There are now 5310 registered users, including 4649 students and 642 teachers. Since going live in 1<sup>st</sup> October 2014 visitors to the site have answered nearly 205,000 questions.



Maps of interactions with Isaac within the last month in the UK and Worldwide



## 2015 Event examples and to come

The teacher and student workshops are major parts of the programme of activities carried out under the IsaacPhysics project. Over the last month, there have been 15 workshops for students and their teachers mainly covering the topics 'Vectors and Exponentials'. These have been held in Birmingham, Cambridge, Essex, Guilford, Oxford, Kent, Leeds (2), London (3), Nottingham, Sheffield, Winchester and York

For updates and details of all our events, see <https://isaacphysics.org/events>

## Promotions



We are delighted to report the promotion of **Mete Atature** (left, Atomic Mesoscopic and Optical Physics) and **John Richer** (centre, Astrophysics) to Professorships and **Claudio Castelnovo** (right, Theory of Condensed Matter) to a Readership. Warmest congratulations to all of them.

## Prizes



We congratulate **Henning Sirringhaus** (left) on being awarded the Institute of Physics 2015 Faraday Medal 'for transforming our knowledge of charge transport phenomena in organic semiconductors as well as our ability to exploit them'.

In the year of his 70<sup>th</sup> birthday celebrations, we are delighted that **Gil Lonzarich** (right) has been awarded the 2015 Kamerlingh Onnes prize for his 'visionary experiments concerning the emergence of superconductivity for strongly renormalised quasiparticles at the edge of magnetic order'. (see pages 2-5).

## Major Research Grants



The European Research Council (ERC) have announced the award of prestigious five year Consolidator Grants to **Andrew Ferguson** (left) in Microelectronics and **Ulrich Keyser** (right) in Biological and Soft Systems.

Andrew's programme is entitled *Quantum magnonics in insulators*. It will build on recent progress in spintronics and solid-state quantum computing in order to measure and control single quantised magnetic excitations known as magnons.

Ulrich's programme has the title *Understanding and designing novel nanopores*. The experiments will combine investigation of driven transport of colloidal particles through microfluidic channels. Since these can mimic the physics of transport through nanometer scale pores found in cell membranes, it gives unique experimental control over transport processes.

## New Appointments

**Ulrich Schneider** Lecturer, Atomic, Mesoscopic & Optical Physics Group (left)

**Tijmen Euser** Lecturer, Nanophotonics Group (centre)

**Saba Alai** Departmental Safety Officer (right)

**Sophia Easey** Assistant Librarian, Rayleigh Library



## Leavers

**Jane Blunt** Departmental Safety Officer

**Joel Brand** Research Grant Assistant, Administration has moved to the School of Physical Sciences to take up the position of Finance Adviser

**Helen Suddaby** Assistant Librarian, Rayleigh Library - retired

**Emily Heavens-Ward** Group Administrator, Microelectronics - maternity leave

We are very sad to report the death of **John Shakeshaft**, former member of the Astrophysics Group and Fellow of St. Catherine's College, at the age of 85. An appreciation of John's life and work will appear in the next edition of CavMag.

## The Fourth Annual Winton Symposium

The Winton Symposium is a major event in the Cavendish calendar that is open for all to attend, the theme for this year is 'Green Computing' and will cover topics ranging from new materials and architectures for low power consumption computing, to computer-based applications which can benefit our environment.

UNIVERSITY OF CAMBRIDGE

THE WINTON PROGRAMME FOR THE  
Physics of Sustainability

Fourth Annual Winton Symposium

**GREEN COMPUTING**

MATERIALS, ARCHITECTURES  
AND APPLICATIONS

One-Day Symposium  
Cavendish Laboratory

**28<sup>TH</sup> SEPTEMBER 2015**

**Dr Mike Lynch**  
Founder, Invoice Capital,  
Co Founder, Autonomy Corporation  
THE GREEN LIGHT FOR NEW COMPUTE:  
WHAT WILL WE NEED ALL THAT COMPUTE FOR

**Professor Andy Hopper**  
Professorial Consultant, Technology,  
Head of Department, The Computer  
Laboratory, University of Cambridge  
COMPUTING FOR THE FUTURE OF THE PLANET

**Dr Krisztian Flautner**  
VP of Research and Development, ARM  
FROM UBIQUITOUS COMPUTING TO THE  
INTERNET OF THINGS AND BEYOND

**Professor Luca Cardelli**  
Microsoft Research and University of Oxford  
MOLECULAR PROGRAMMING

**Professor Linda Nazar**  
Department of Chemistry, University of  
Waterloo, Canada  
TITLE TO FOLLOW

**Professor Hideo Ohno**  
Laboratory for Nanoelectronics and Spintronics,  
Tohoku University, Japan  
NONVOLATILE VLSI MADE POSSIBLE BY  
SPINTRONICS

For free registration, go to [phy.cam.ac.uk/greencomputing](http://phy.cam.ac.uk/greencomputing)

Continued from overleaf..



Two members of the Cavendish Laboratory have been recognised by the Royal Society for their achievements in research.

**Benjamin Simons** (Theory of Condensed Matter Group and CRUK Gurdon Institute, left) has received the Gabor Medal for his work analysing stem cell lineages in development, tissue homeostasis and cancer, revolutionising our understanding of stem cell behaviour *in vivo*.

**Russell Cowburn** (Thin Film Materials Group, centre) has received the Clifford Paterson Medal and Lecture for his remarkable academic, technical and commercial achievements in nano-magnetics.

## Congratulations

We congratulate **Michael Gates** (right) most warmly on his appointment as the Lucasian Professor of Mathematics, the successor to Michael Green, Stephen Hawking and Paul Dirac. He was an assistant lecturer and then lecturer in the Laboratory from 1989 to 1995.



### The Topping Out ceremony of the Maxwell Centre

took place on 31 March 2015. At the front of the gathering are (left to right): Francis Shiner (Managing Director, SDC Builders Ltd) Richard Friend, Lynn Gladden (Pro-Vice-Chancellor for Research) and Andy Parker.

## HOW YOU CAN CONTRIBUTE

### » Online Giving

The University's Office for Development and Alumni Relations 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](http://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](http://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](http://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](http://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](http://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 Professor Malcolm Longair ([mssl1000@cam.ac.uk](mailto:mssl1000@cam.ac.uk)) or Mr Robert Hay ([rach2@cam.ac.uk](mailto:rach2@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 **Professor Malcolm Longair** ([mssl1000@cam.ac.uk](mailto:mssl1000@cam.ac.uk)) or **Professor Andy Parker** ([hod@phy.cam.ac.uk](mailto:hod@phy.cam.ac.uk)), who will be very pleased to talk to you confidentially.

## CONTACT

**The Cavendish Laboratory**  
JJ Thomson Avenue  
Cambridge  
CB3 0HE

Tel: +44 (0)1223 337200  
Fax: +44 (0)1223 363263  
Email: [hod@phy.cam.ac.uk](mailto:hod@phy.cam.ac.uk)  
[www.phy.cam.ac.uk](http://www.phy.cam.ac.uk)

**Head of Department**  
Professor Andy Parker  
Tel: +44 (0)1223 337429  
Email: [hod@phy.cam.ac.uk](mailto:hod@phy.cam.ac.uk)

**Director of Development**  
Professor Malcolm Longair  
Tel: +44 (0)1223 765777  
Email: [mssl1000@cam.ac.uk](mailto:mssl1000@cam.ac.uk)