Spring 2016, Number 8

Department of Physics Newsletter

TRAPPING A STAR IN A MAGNETIC DOUGHNUT

The physics of magnetic confinement fusion

RATTLING THE CAGE:

Making new superconductors using lasers

DARK MATTER IN OUR GALAXY

Novel dynamics is bringing the Galaxy's dark matter into much sharper focus

LIGO

and gravitational waves: a personal reaction

ALUMNI STORIES

Richard JL Senior and Elspeth Garman reflect on their experiences

EVENTS

Remembering Dick Dalitz; Oxford celebrates Nobel Prize; Physics Challenge Day and many more events

PEOPLE

Five minutes with Geoff Stanley; Awards and Prizes

www.physics.ox.ac.uk

DARK MATTER IN OUR GALAXY

In the Rudolf Peierls Centre for Theoretical Physics novel dynamics is bringing the Galaxy's dark matter into much sharper focus

Prof James Binney FRS

In 1937 Fritz Zwicky pointed out that in clusters of galaxies like that shown in Fig. 1, galaxies move much faster than was consistent with estimates of the masses of individual galaxies based on the speeds at which stars move within the galaxies. Zwicky argued that the gravitational field generated by the galaxies is a factor of several too weak to prevent the galaxies flying off into intergalactic space and the clusters dissolving within a gigayear or so.

In the late 1970s Vera Rubin and her colleagues measured the rotation speeds of significant numbers of galaxies like ours and argued that the speeds didn't decline with distance from the centres of the galaxies as fast as you would expect. Around that time it was concluded that galaxies, such as ours, which belong to small groups, have relative velocities that are larger than is consistent with the galaxies moving in the gravitational field that the stars generate, and the idea took root that galaxies are embedded in 'halos' of 'dark matter'. Dark matter became the prevailing orthodoxy at a meeting held at Yale in the summer of 1977.

It turned out that Rubin's measurements of stellar velocities didn't extend far enough from galactic centres to prove that stars don't dominate galaxies. The clinching evidence that there is much more to a galaxy than stars and gas was delivered in 1985 by the PhD thesis of Dutch student Kor Begeman, who used the Westerbork Radio Synthesis Telescope to trace clouds of hydrogen to large distances from the centre of NGC 3198. The data showed that gas clouds moved on perfectly circular orbits at a speed that was essentially independent of radius r, even way beyond the last star in the galaxy. If the gravitational field that keeps the clouds on circular orbits were largely generated by stars, the speed of rotation would be falling as $1/\sqrt{r}$ just as the orbital speed of planets falls with distance from the Sun. For the rotation speed to be independent of radius, as Begeman found, the density of matter around the galaxy would have to be inversely proportional to the square of distance: $\rho \propto 1/r^2$.

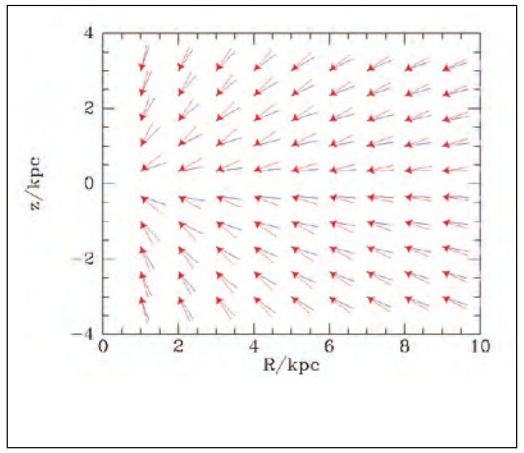
WHERE'S OUR DARK MATTER?

In the 1980s black holes and neutrinos were viable candidates for the mysterious dark matter. By the end of the 1980s simulations of the gravitationally induced clustering of neutrinos before galaxies formed had shown that dark matter could not be made of neutrinos, because they are individually too light. A variety of arguments later ruled out black holes with masses larger than that of a planet as the source of dark matter. Other known objects, such as low-mass stars, planets and white dwarfs have also been excluded. So we don't know what dark matter is, but it accounts for four fifths of all matter, and a dark matter particle has to have an exceedingly small probability of colliding with either ordinary matter or another dark matter particle. The only mode of interaction dark matter certainly possesses is gravity. People hope that it is capable of 'weak' interactions (really exceedingly short-range interactions) because that gives hope of actually detecting a dark matter particle here on Earth, but nature could be unkind and deny dark matter even weak interactions.

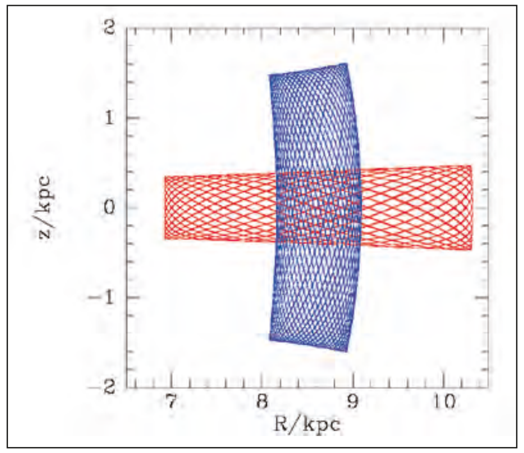
Figure 1. The galaxy cluster Abell 2218 imaged by the Hubble Space Telescope.

SCIENCE NEWS
www.physics.ox.ac.uk/research

Right: Figure 2. The red arrows show the direction of the Galaxy's gravitational field by our current reckoning. The blue lines show the direction the field would have if the disc were massless. The mass of the disc tips the field direction towards the equatorial plane. A more massive disc would tip it further.



Far right: Figure 3. The orbits in the R_z plane of two stars that both move past the Sun with a speed of 72 km s^{-1}.



Even though we are able to study our own Galaxy in vastly greater detail than external galaxies, our location within the Galaxy makes it hard for us to establish the existence of dark matter in our Galaxy. Specifically, dark matter becomes dynamically dominant far from the centres of galaxies, and it is hard to measure accurately the kinematics of objects that lie further from the Galactic centre than the Sun does.

Some of the best work that has been done on the kinematics of objects that move through the region of dark matter dominance far from the Galactic centre was done in Oxford around 2000 by Wyn Evans (now in Cambridge) and his students. They showed that the data were consistent with the Galaxy having a dark halo analogous to that detected around external galaxies, but the mass of any dark halo was uncertain by a factor of several.

In the last five years we have used the dynamics of relatively nearby stars to constrain the mass of the part of the dark halo that lies interior to the Sun. We were members of an international collaboration which obtained the spectra of almost half a million stars at the Anglo-Australian observatory. We developed a Bayesian algorithm to determine the distances to these stars from the spectra and previously published measurements of brightnesses and colours. The velocity of each star along our line of sight was available from the spectra, and knowing the distances enabled us to infer velocities perpendicular to the lines of sight from the stars' proper motions (motions across the sky), which had been measured by the US Naval Observatory.

To complement these kinematic data, we needed information about the spatial distribution of the population of stars that had been probed by our spectroscopic survey. We took this from an analysis of a large US photometric programme, which had counted hundreds of millions of faint stars as a function of brightness and colour.

The physical principle we exploited to measure the interior mass of the dark halo is this: we approximate the Galaxy by an axisymmetric system and use cylindrical polar coordinates, with R distance from the symmetry axis and z distance from the Galaxy's equatorial plane. The dark halo and the disc both pull the Sun towards the Galactic centre, and thus help determine the speed v_c of a circular orbit at the distance of the Sun from the Galactic centre R_0. So a given 'rotation curve' $v_c(R)$ can arise from a massive disc and a light dark halo, or from a light disc and a massive dark halo, or any intermediate configuration. What distinguishes between these possibilities is the vertical extent of the disc: if the disc is massive, the gravitational force K_z towards the equatorial plane that a star distance z from the plane experiences will rise much more rapidly with z than if the disc is light, because the disc's matter is concentrated around the plane while that of the dark halo isn't (Fig. 2).

The disc has a non-zero thickness because its stars have random velocities in addition to a shared streaming velocity around the Galactic centre. The larger the random velocities are, the thicker a disc of a given mass will be. So by combining knowledge of how the number density of stars declines with z with measurements of the random velocities of stars, one can determine the mass of the disc.

OUR INNOVATIONS

This idea is an old one, but we implemented it with new data and a new approach to dynamics. A star with a given amount of angular momentum L_z about the symmetry axis can be considered to move in the (R, z) plane as shown in Fig. 3. The horizontal and vertical limits of this motion can be set independently. In fact, they are determined by two 'constants of motion' J_r and J_z that characterise the orbit. Any non-negative function $f(J_r, J_z, L_z)$ (a 'distribution function'), interpreted as the phase-space density of stars, together with a model of the Galaxy's gravitational potential $\Phi(\mathrm{x})$ specifies a steady-state model Galaxy. We developed techniques that enable us to compute from f and Φ the number density of stars, $\rho_n(\mathrm{x})$, at any spatial point x, as well as the distribution of stellar velocities, $n(\mathrm{v})$, at that point.

Around 2010 we showed that for plausible forms of Φ, very nice fits to observational estimates of $\rho_n(\mathrm{x})$ and

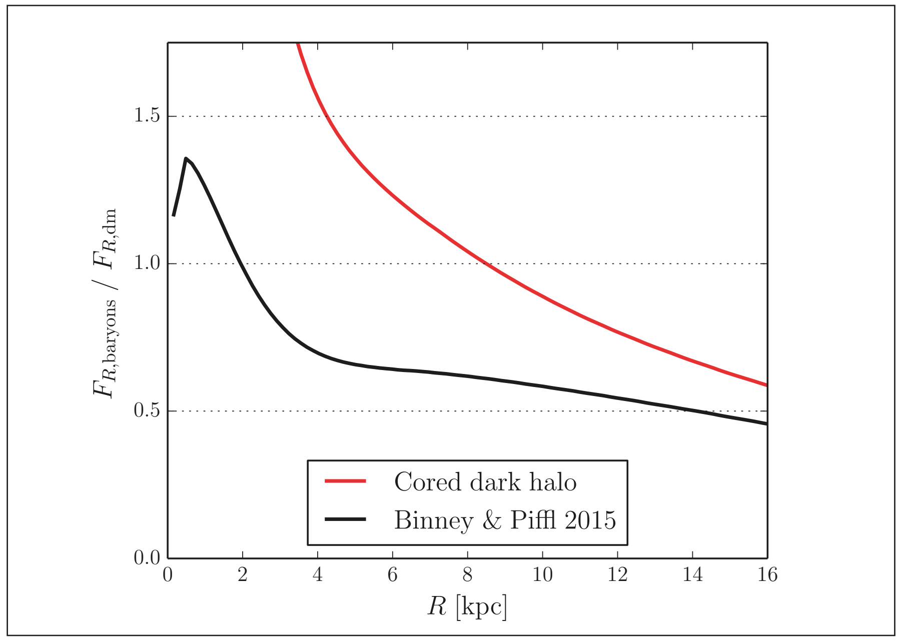
$n(v)$ are provided by simple analytic forms of $f(J_r, J_z, L_z)$. This discovery suggested the next step should be to adopt flexible parametric forms for f and Φ and to search the space of parameters for (f, Φ) pairs that yield $\rho_n(x)$, and $n(v)$ at various locations that are consistent with the data.

As we search for (f, Φ) pairs, we should be mindful that a major contribution to Φ comes from the mass density of stars ρ_m. That is, Φ should not be considered entirely independent of f. In our work on this problem two years ago we acknowledged this dependence in a rough way: we fitted $\rho_n(x)$ by a sum of two functions of the form $\exp(-R/R_d - |z|/z_d)$, which for certain values of the scalelengths R_d and z_d fits the data rather well. Then multiplying this number density by an estimate of the mean stellar mass, we used the analytic potential generated by this fit as the disc's contribution to Φ. This rough treatment sufficed because at that stage we were using a very weak prior for the contribution of dark matter to Φ. In fact, we were adopting an empirical fit – the 'NFW' profile – to the density distribution of dark matter in simulations of the cosmological clustering of dark matter in the absence of ordinary matter – adding ordinary matter to a cosmological simulation opens a Pandora's box of difficulties and hugely increases the computational resources required. In fact, it is still unfeasible to include all the physics that's relevant in a simulation that includes ordinary as well as dark matter.

ORDINARY MATTER MODIFIES DARK MATTER

For a decade or so it has been standard procedure to model galaxies using the NFW profile for the dark matter, as we did until recently. But this procedure is unsatisfactory because the NFW profile is based on simulations that contain no ordinary matter and the distribution of dark matter will certainly be modified by the gravitational attraction of ordinary matter: dark matter will be pulled in towards the Galactic centre and down towards the plane. Using our technology for computing the constants of motion J_r and J_z we can estimate this distortion by assigning the dark matter a distribution function $f(J_r, J_z, L_z)$ similar to that of the stars. With both the dark matter and the stars represented by distribution functions, Φ becomes something that is computed from the distribution functions rather than something that is posited. So now, given any distribution functions for the stars and the dark matter, we can compute the observables ρ_n and $n(v)$ and adjust the distribution functions until they agree with the data.

The snag is that a great many CPU cycles are now required to compute ρ_n and $n(v)$ because we have to determine ρ_m everywhere in the Galaxy, from the Galactic centre to points 300 000 light years from there, where much of the dark matter resides. And we have to compute this density five times because we determine the potential Φ implied by the distribution functions iteratively: guess Φ, compute the consequent density distribution, compute the potential implied by this



distribution and then recompute the density using this Φ until Φ changes negligibly at each iteration.

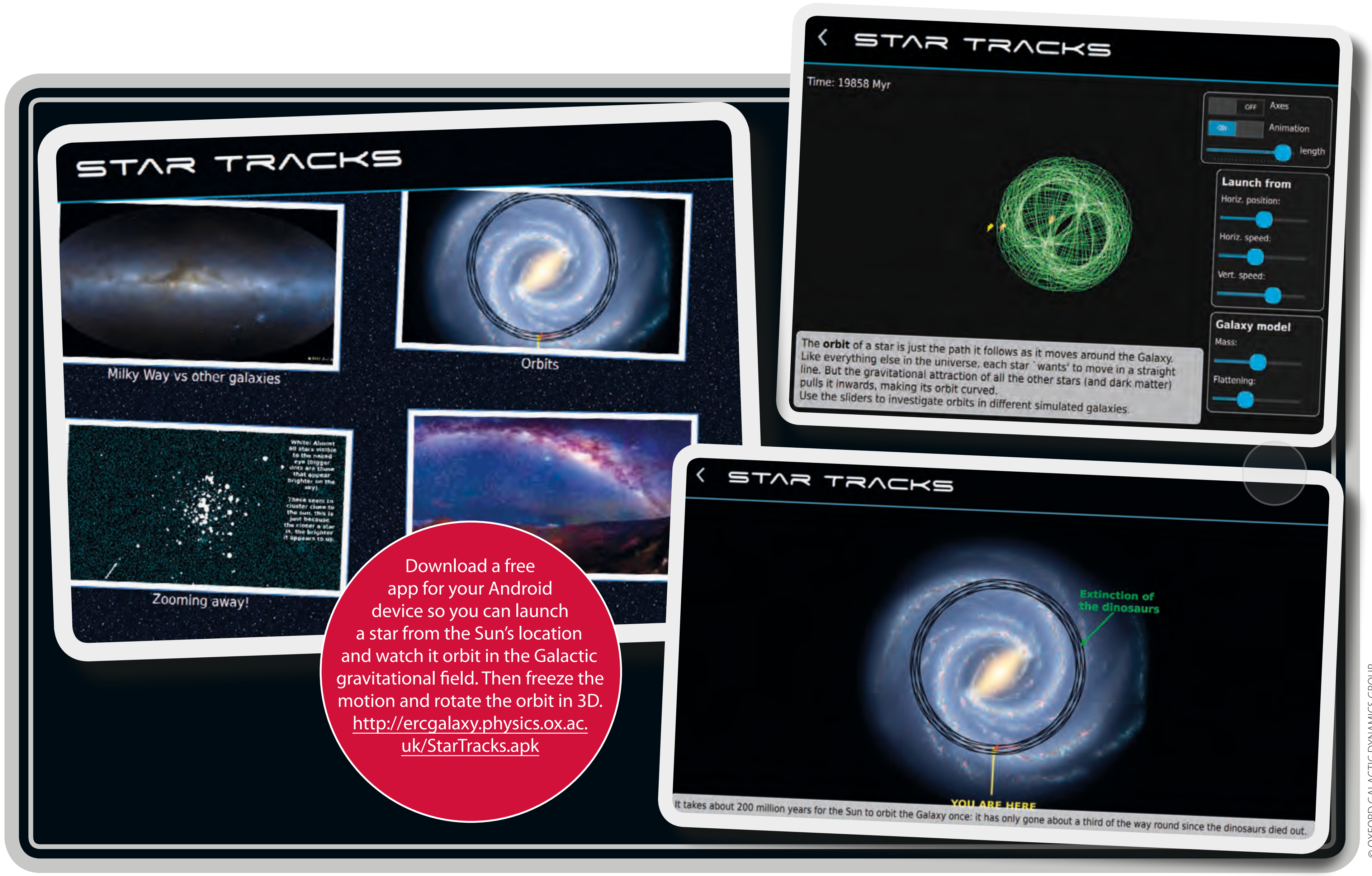
On account of the computational cost, we have yet to explore adequately the space of possible distribution functions. In our first effort we fixed the distribution function of the dark matter from a variety of cosmological constraints and searched the space of stellar distribution functions for one that was compatible with the rotation curve $v_c(R)$, the vertical density profile $\rho_n(z)$ of stars above the Sun, and the velocity distributions $n(v)$ at eight points near the Sun. The computer found a model that satisfied all these constraints, but violated a constraint the computer hadn't been told about.

This constraint is the probability P_{len} that a star seen towards the Galactic centre is 'gravitationally microlensed'. During a microlensing event, the gravitational field of a foreground star briefly focuses the light from the background star so the latter appears significantly brighter. P_{len} varies with position on the sky, but near the Galactic centre in Sagittarius it is of order 10^{-6}, so at any given time one star in a million is being microlensed. The wonderful thing about microlensing is that P_{len} doesn't depend on the size of the lumps that make up a given mass density ρ: P_{len} is the same whether the lumps are Jupiters, Suns or massive black holes; increasing the mass of the lumps simply increases the duration of each microlensing event with a compensating reduction in the number of events per unit time. In practice there is a minimum mass, comparable to the Earth's mass, required to generate a detectable event, because events that are over very quickly won't be detected. The first application of searches for microlensing events was to show that dark matter cannot be invested in black holes or planets because such objects would cause stars in the Magellanic Clouds to be microlensed more often than is observed. So dark matter, unlike ordinary matter, cannot contribute to the measured value of P_{len} in fields near the Galactic centre.

Opposite page: Figure 4. The ratio of the gravitational force at radius R in the disc from ordinary and dark matter in two models. The model yielding the red curve takes into account the expected impact of the bar on dark matter, while the black curve is for a model that neglects such impact.

The model we made using the cosmologically motivated distribution function for dark matter, predicted a value of P_{len} that is significantly too small. It also yielded a value of the radial scalelength of the stars, R_d that is larger than that obtained by counting stars. Both of these shortcomings reflect the model's dark halo being too centrally concentrated because it has been pinched in by the gravitational attraction of the stars. The black line in Fig. 4 shows for this model the ratio of the gravitational forces from ordinary and dark matter at radius R in the disc. Ordinary matter contributes less than dark matter outside $R = 2$ kpc. In this model the distribution function of the dark matter fails to take account of the impact that the Galaxy's rotating bar has had on dark matter: dark matter particles will have picked up energy and angular momentum from the rotating gravitational field of the bar, leading to a reduced phase-space density of dark matter at small values of J_r, J_z and L_z. The red curve in Fig. 4 shows the ratio of gravitational forces from ordinary and dark matter in a model we have just constructed using a distribution function for the dark matter that allows for the impact of the bar. Now ordinary matter contributes more to the gravitational force inside 8 kpc, roughly the radius of the Sun's orbit. Consequently, this new model predicts an acceptably high value of P_{len}, and, as a bonus, the scalelength R_d of the disc is now consistent with star counts.

In another line of attack on these issues we have been using N-body models to study the growth of the Galaxy over the last ~ 10 gigayears. These models have cast a bright light on the way in which molecular clouds, the bar and spiral arms drive evolution of the stellar distribution function. They will also show how ordinary matter modifies the distribution function of dark matter, but we have yet to extract this information. We are excited to see whether there is good agreement between this evolution and the difference between our original cosmologically motivated distribution function and the distribution functions we find to be consistent with all current observational data. ■



TRAPPING A STAR IN A (MAGNETIC) DOUGHNUT

THE PHYSICS OF MAGNETIC CONFINEMENT FUSION

Prof Michael Barnes

One gram of hydrogen heated to one hundred million degrees for one second. Roughly speaking, this is the goal of magnetic confinement fusion research. Why? Because that is what's required to generate enough fusion reactions between the hydrogen nuclei to sustain the temperature needed to generate more fusion reactions. Does it sound doable? One hundred million degrees is quite hot (hotter than the hottest spot in the Sun), but we only need to heat one gram for one second, so how hard can it be? Physicists have been pursuing this holy grail of renewable energy for several decades now, and there is still no Mr Fusion powering our Delorians. So clearly it's not so easy. However, we are finally close to demonstrating the technical feasibility of magnetic confinement fusion.

First of all, let me say this: Even though we aren't living in a fusion-powered utopia at the moment, magnetic confinement fusion does work. We can heat about a gram of hydrogen up to one hundred million degrees and produce fusion energy. We can confine the hydrogen for longer than a second. We just can't do them both at the same time yet. As a result, we currently have to use slightly more energy to start and maintain the process than we can usefully obtain from the fusion reactions. The best we've done so far is to get out about 95% of the energy we put in, and this was achieved at the Culham Science Centre just a few minutes drive from Oxford. However, a machine currently being built in France (ITER) is predicted to produce ten times as much energy as we put in.

To understand the origin of this extra factor of ten in the ratio of output to input power, we need to understand how magnetic confinement fusion works. It turns out that heating hydrogen to one hundred million degrees is the easy(ish) part. It is achieved through a combination of running a current through the plasma (Joule heating) and then either blasting the plasma with a high energy beam of neutral particles or injecting radio frequency waves to resonate with the Larmor motion of the charged particles in the plasma. The challenge is then how to maintain this extreme temperature.

As we all know, a gas expands to fill the volume of its container, and the expansion rate increases with temperature. At one hundred million degrees, it would take about a microsecond for an initially localised hydrogen gas to fill the volume of current experiments. This problem is overcome in the case of the Sun and other stars because their large mass provides a strong gravitational force that balances the outwards force exerted by the pressure from the hydrogen gas. Since we have no convenient source of solar-level mass in the lab, we have to make use of another property of the high temperature hydrogen gas: the fact that it is not really a gas at all.

When the hydrogen gas is heated to a temperature high enough that its thermal energy is larger than the atomic binding energy for hydrogen (several thousand degrees), the bond of each electron to its respective atom is broken. This means that the hydrogen gas is now ionized, with electrons and hydrogen nuclei free to move independently. Such an ionized gas is called a plasma and is considered to be a distinct state of matter. Why make this distinction? Because the fact that the charged particles in a plasma generate and respond to electromagnetic fields leads to a wide range of complex, collective behaviour that is qualitatively different from the behaviour of a (neutral) gas.

MAGNETISED PLASMA DYNAMICS

Dealing with a plasma instead of a gas complicates our lives as physicists, but it also provides us with the key we need to confine hydrogen at high temperatures. We know that the trajectory of charged particles is modified in the presence of a magnetic field due to the Lorentz force. The Lorentz force constrains charged particles to circle around magnetic field lines: the stronger the magnetic field, the smaller the circle. So if we apply very strong magnetic fields (several Tesla), then all we need to do is bend the magnetic field lines to form a closed surface (a torus) and – voilà – the plasma is confined.

Unfortunately, that's not the whole story. Charged particles are mostly constrained to follow magnetic field lines, but the curvature and inhomogeneity in the imposed magnetic field (needed to form closed magnetic surfaces) effectively exert additional forces on the particles that cause them to slowly drift across the magnetic field. Cleverly constructed magnetic field lines that twist helically as they traverse the torus can cancel this drift (particles spend equal amounts of time drifting out and in so there is no net motion across field lines). However, put a large enough gradient in the density or temperature of the plasma, and these drifts give rise to instabilities that produce turbulent fluctuations of the plasma. Turbulent eddies then mix hot, dense plasma near the centre of the confinement volume with cold, dilute plasma near the edge, limiting the central temperature and density – and thus the fusion power that can be produced.

So why is the next generation fusion experiment (ITER) expected to provide a factor of ten improvement in energy production? The answer is of course complex, but a big part of this improvement is simply because the plasma diameter in ITER will be (at least) twice the size of the plasma diameter in current experiments. This means that it takes longer for turbulence to diffuse heat out of the plasma (so the central temperature can be higher) and that there will be a larger plasma volume producing fusion energy. Making the experiment larger seems like a simple solution to our problem, but it comes at a cost. Literally – the price tag on ITER is somewhere in the neighborhood of £20 billion. Some of that cost comes from the fact that it's the first experiment of its kind and requires the development of new technologies and pushes the boundaries of existing technologies. However, part of the cost comes from the fact that the price of an experiment like this increases roughly with its volume. What this means is that if we want to make fusion economically competitive, there is work we need to do as physicists to limit the size of an eventual reactor.

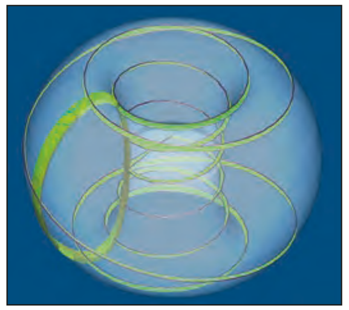


Fig. 1: Turbulent fluctuations of plasma density at one radial location in a toroidal fusion device. Simulation domain elongated along magnetic field due to anisotropy of the turbulence.

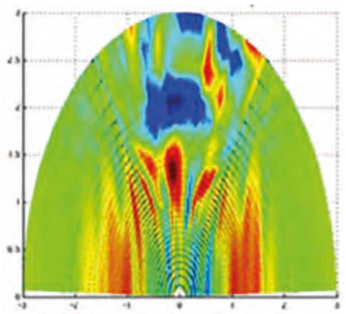
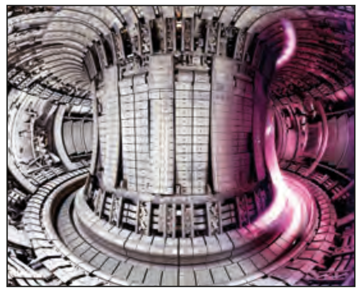


Fig. 2: Turbulent fluctuations in the distribution of particle velocities parallel and perpendicular to the magnetic field.



EUROFUSION

A section of plasma (in pink, its actual colour under these conditions) superimposed on the interior of the Joint European Torus (JET).

KINETIC EFFECTS AND TURBULENCE

That's what we are working on in the Plasma Theory Group at Oxford. In particular, we are studying the properties of magnetized plasma turbulence so we can understand how it works, predict how it will impact fusion plasmas, and determine what we can do to minimize its deleterious effect on magnetic confinement. Treating plasma turbulence in these systems is challenging: the fact that it is plasma turbulence means we have to include the effects of electromagnetic fields, and the fact that the temperature is so high means that 'collisions' between particles due to Coulomb interactions happen infrequently. Consequently, we cannot treat the plasma as a fluid; instead, we have to use kinetic theory.

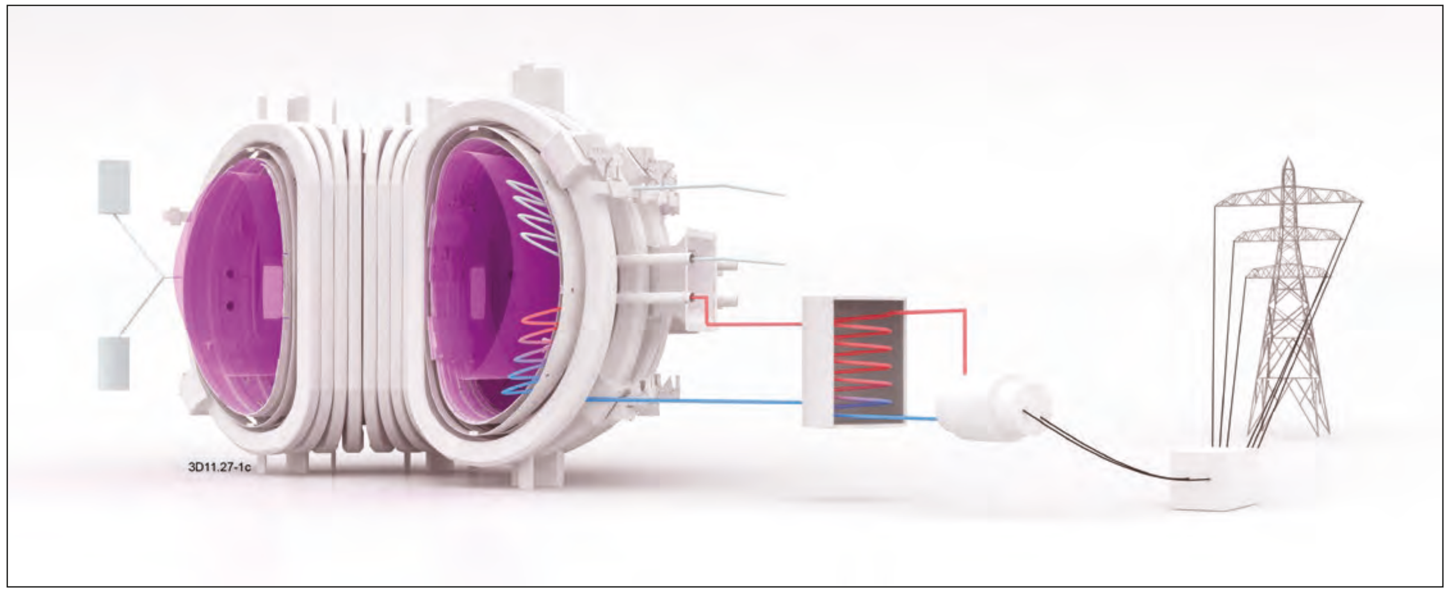
Directly solving the equations of motion either analytically or numerically for the 10^{20} or so particles that make up the plasma is not remotely feasible. Instead we follow the distribution of particle positions and velocities, which satisfies a conservation equation in the six-dimensional phase space. We simplify this kinetic equation further by making use of the fact that the gyromotion of particles about the magnetic field is much faster than any other phenomena of interest to us. This 'gyrokinetic' approximation allows us to eliminate the angle of gyration as a phase space variable; thus, we only follow the motion of charged 'rings' that stream along the magnetic field and slowly drift across it.

MAGNETISED PLASMA TURBULENCE RESEARCH AT OXFORD

Armed with the gyrokinetic equation and a low-frequency version of Maxwell's equations, we use a combination of analytical and numerical approaches to determine how the turbulence behaves. Simple conjectures about turbulence characteristics can be made to provide predictions for how the energy contained in the fluctuations is distributed amongst different phase space scales and how turbulent fluxes of particles, energy, and momentum depend on experimental inputs such as magnetic geometry and applied torque. These conjectures can be tested with direct numerical simulations, which evolve the particle distribution function in phase space and time. To make these simulations possible, we utilize advanced algorithms that take into account the facts that the turbulence evolves on much smaller space-time scales than the equilibrium (which lets us focus on one patch of the plasma at a time) and that the strong magnetic field makes the turbulence anisotropic (particles stream freely along but slowly across the field, and the turbulence structure reflects this). It also helps that we are able to run our simulations on the world's fastest supercomputers. A snapshot of what plasma turbulence in one of the fusion experiments at the Culham Centre for Fusion Energy looks like is shown in Figs 1 and 2.

With analytic results guiding us and numerical simulations allowing us to probe the turbulence, we are trying to understand such questions as why some regions of the plasma are observed in experiments to be turbulence-free and why fusion plasmas spontaneously start to rotate without any applied torque. Hopefully the results we find will help make eventual fusion reactors a bit more economical and bring the fusion-powered utopia closer to reality. ■

Below: Sketch of a fusion power plant. Hydrogenic gas is heated inside a torus-shaped magnetic confinement device to over one hundred million degrees. Resultant plasma (indicated in pink) undergoes fusion reactions that generate energetic neutrons. The energy from these neutrons is captured and used to heat water, which turns a turbine and generates electricity for the grid.



EUROFUSION

SCIENCE NEWS
www.physics.ox.ac.uk/research

RATTLING THE CAGE:
MAKING NEW SUPERCONDUCTORS USING LASERS

One of the most remarkable and unexpected scientific discoveries of the 20th century is that when some materials are cooled below a characteristic critical temperature they become superconductors. The 'super' is well earned since in this state materials can carry electrical current with exactly zero resistance while simultaneously expelling any magnetic fields that might penetrate them. Elevating this miraculous phenomenon to room temperature has been the subject of intensive efforts in physics for many decades. Yet it has remained stubbornly out of reach. Even the best so-called 'high temperature' superconductor is still an elusive factor of two from this goal. Very recently experiments based at the Max Planck Institute for the Structure and Dynamics of Matter in Hamburg have pioneered a new technique for inducing superconductivity by shining laser light on to a material. In work reported in the journal *Nature* in February, compelling evidence was found showing how this approach can make a material superconduct far above its critical temperature. This fascinating observation promises to open up new pathways for engineering superconductivity.

There were numerous contrasting theories about what happens close to absolute zero at the time. None predicted what actually happened.

The story of superconductivity emerged from some of the first experiments reaching temperatures nearing absolute zero. In 1911 Kamerlingh Onnes began investigating what happens to the electrical resistivity of metals at very low temperatures. Normal conductors like metals always have some resistance to electrical current because mobile electrons scatter off the jiggling positive ions making up the material. There were numerous contrasting theories about what happens close to absolute zero at the time. None predicted what actually happened. Onnes found that the resistance of mercury vanished abruptly when cooled with liquid helium.

SUPERCONDUCTIVITY – WHAT'S THE FUSS?

It took more than 50 years, and numerous Nobel prizes, for a satisfactory explanation of this effect to be found. This theory posits that superconductivity occurs because mobile electrons in a solid can have a very weak attraction between them. This sounds odd since we are all used to like charges, such as two electrons, strongly repelling one another. This is certainly true if the electrons are brought close together. However, when an electron whizzes past the positive ions it attracts them towards it leaving a wake of disturbed positive charge that takes some time to relax. Consequently another electron passing through the same region some time later can be caught up in the wash left behind by the first. This attraction is enough to create a weak but long-ranged tether between electron pairs. Electrical resistance vanishes because unlike single electrons the motion of these pairs is very robust to scattering off ions. Unfortunately this theory made it clear that superconductivity was unlikely to ever occur much above 20 K.

This all changed in the mid 1980's when an entirely new class of superconductor that worked at 35 K was discovered in ceramic-like materials called cuprates. In the years that followed this the ceiling was smashed completely with new variants operating at 138 K, hot enough that cheap coolants like liquid nitrogen could be used. They were coined 'high temperature superconductors'. This triumph left us only a factor of 2 from room temperature so naturally there was a strong expectation that this would follow shortly.

One might ask why getting to room temperature matters. We only need to look back as far as the 1950s to see how the physics of novel materials can be technologically transformative. The creation of semiconductors, and devices like transistors built from them, was the foundation of the entire digital world we now take for granted daily. There is little doubt that the creation of a room temperature superconductor would usher in a similar technological revolution. Superconductors already find applications in power storage and transmission, and are ubiquitous in magnetic hospital scanners. Moreover, they are central to magnetic levitation transportation used in Japanese Mag-Lev trains. Reaching room temperature would not only hugely refine and extend these applications, but could even herald new technologies such as ultra-fast switches that could potentially replace the mighty transistor.

Yet this gap to room temperature has not been closed so far. Partly this is because of the immense plethora of possible cuprate materials to explore. Also it is because these new materials were quickly revealed to superconduct in a different way to the conventional ones described above. Consequently the standard theory does not apply and it is still far from fully understood how these materials work.

MATERIALS MADE FROM BUCKY-BALLS

The recent Hamburg experiment investigated a particular material built out of bucky-balls, which are large molecules composed of 60 carbon atoms arranged in a football-like cage, denoted as C_{60}. When squashed together, bucky-balls form a regular solid, one layer of which is shown in the figure below. When composed only of bucky-balls this material is a fairly boring insulator, ie does not easily conduct electricity a bit like rubber. Things get much more interesting if other atoms are added into the mix, especially alkali atoms like potassium, whose chemical symbol is K. We can imagine these atoms as ping-pong balls filling up the spaces between a big pile of footballs, and it turns out there is space for three times as many of them as bucky-balls, so we end up with K_3C_{60}. What is special about potassium and other alkali atoms is that they have a single valence electron, and this generally makes them very chemically reactive. As such, the potassium atoms readily donate their valence electron to the bucky-balls, giving them three each. These liberated electrons are then free to hop from one bucky-ball to another through the material, making it metallic at room temperature. However, the most striking feature occurs when the material is cooled down: below 20 K the system becomes a superconductor.

Dr Stephen Clark, Lecturer, Department of Physics, University of Bath

Prof Andrea Cavalleri

Prof Dieter Jaksch

SHAKING THE RIGHT NOTE

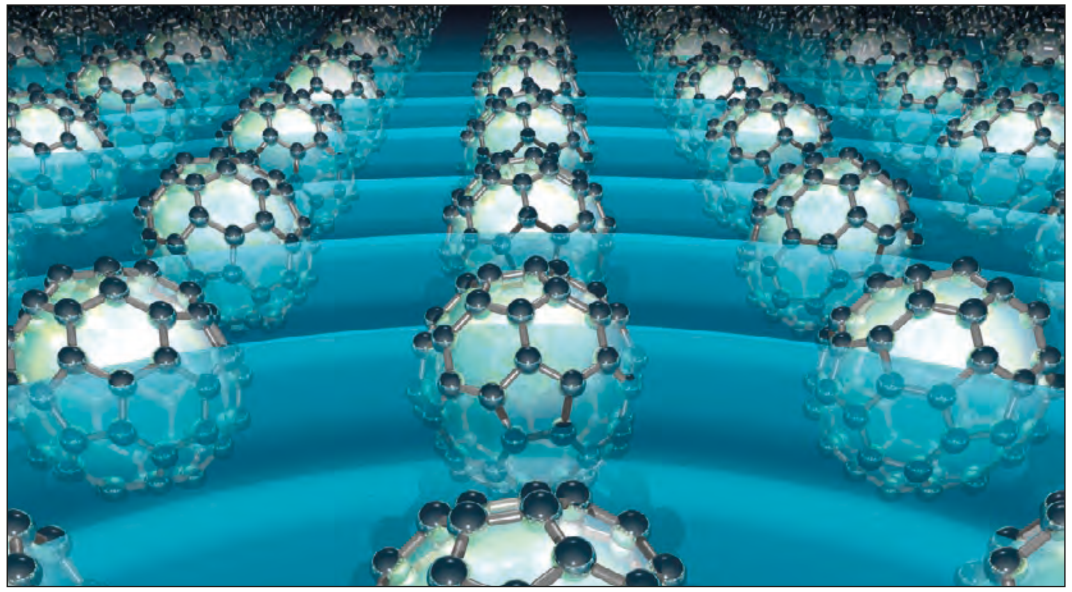
An intriguing feature of molecular solids like K_3C_{60} is that their building block, in this case a bucky-ball, possesses many vibrational modes. These modes are like notes of a guitar string, except these vibrations correspond to distortions of the carbon cage akin to stretching and compressing a football. In the experiment, a powerful laser was used to generate very short pulses at a frequency that is resonant with one of the bucky-ball vibrational modes. This meant that the laser was tuned just right to pluck a particular note of the bucky-ball, and was sufficiently intense to make this note ring with sizeable amplitude. By shining the laser on K_3C_{60} material, all the bucky-balls in the lattice start to shake in unison. Another, much weaker, laser pulse was then used, which scanned across many frequencies, to probe how the material behaved. This is where things started to get curious. At a 100 K, where K_3C_{60} is a normal metal, we found that so long as the bucky-balls were vibrating the optical response measured by the probe pulse looked almost identical to that expected of a textbook superconductor.

Rattling the carbon cage thus appeared to have coerced the material to behave like a superconductor at far higher temperatures than it does naturally. This unusual behaviour disappeared progressively as room temperature was approached. Notably, below 20 K – where the material was already a superconductor – we found that driving the vibration actually destroyed superconductivity. This last observation therefore suggests that the 'induced' superconductor is not just the naturally occurring one on steroids. Rather, it is a completely different type of superconductor better suited to higher temperatures, and a very antagonistic bedfellow with its low temperature cousin.

THE PATH AHEAD

So what is going on here? The short answer is that we do not know yet. However, work with collaborators in Paris is investigating a number of likely causes. Rattling the carbon cage may be enhancing the 'glue' between electron pairs by distorting very slightly the lattice structure, or, because it causes the valence electrons to slosh around the surface of the bucky-ball, changing the way they interact with one another.

Perhaps the most important feature of this experiment is that it opens up new knobs and levers from which we can control and manipulate superconductivity. This not only complements the immensely important on-going work producing new materials, it also provides new windows into the underlying phenomenon. This is crucial since there is still much to be understood about superconductivity and its many guises. While blasting a slab of material with a laser is probably not our 'dream' room-temperature superconductor, inducing one is nonetheless useful. It will likely reveal helpful clues about how we might go about fabricating a material that superconducts without needing the laser. Shaking bucky-balls and other materials is thus a small step towards realising the superconductor revolution. ■



In solids bucky-balls are arranged in a face-centred cubic lattice. One layer is depicted here. The intense pump laser pulse then excites a vibration of each bucky-ball in the lattice.

LIGO AND GRAVITATIONAL WAVES: A PERSONAL REACTION

I was very pleased and excited to hear the news from LIGO in February: the first direct detection of gravitational waves. These waves are sometimes called waves in spacetime itself, though one can equally well regard them as waves in a gravity field which extends throughout spacetime. However you see it, their detection opens up a new era in astronomy. In a loose comparison, it is as if up to now we have been able to see the universe, and now we are beginning to be able to hear it too.

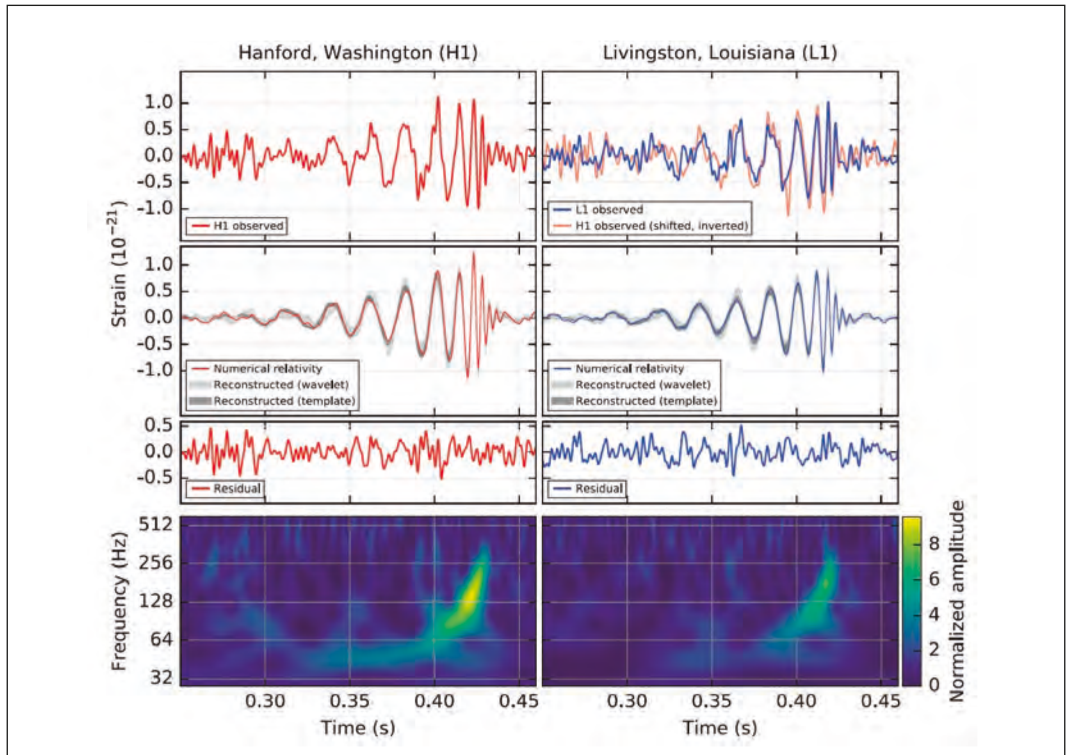
The scientific paper describing the observations can be found here: http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.061102 and there is a well-written viewpoint article here, which helps to assess what has been done: http://physics.aps.org/articles/v9/17. I will offer some reflections on this.

It is not quite true to say that there was no previous evidence of gravitational waves, because their presence had been inferred with reasonable confidence from the behaviour of a binary neutron star system called the Hulse-Taylor pulsar. However, this previous work did not detect the waves themselves; rather, the rate of loss of energy in the system was deduced from observations of the timing of the orbit, and the expected rate of loss of energy was calculated from the theory of General Relativity, and the two agreed. The new observation is very different. This time, an oscillation in spacetime passed across planet Earth and was directly detected by two large instruments in America.

MOUNTING EXCITEMENT

The scale of this achievement can be measured in various ways. The oscillation that was detected was one which moved a pair of mirrors through distances much smaller than the size of an atomic nucleus. To any scientist, this is mind-boggling, because the atomic nucleus is so small that one cannot imagine an instrument sensitive enough to detect such a motion. One cannot, that is, unless one undertakes a decades-long planning and implementation programme to show that it can be done. In this case the mirrors are used to reflect laser beams which bounce many times between them, enhancing the signal, and the mirrors are scrupulously protected from other sources of vibration. Each 40 kg mirror hangs from a large cylinder which in turns hangs from a further double-pendulum, the whole supported by a platform whose motion is servo-controlled via an active seismic isolation system. To estimate the background noise, one has to allow for things like rabbits running around on the ground near the detector (each detector itself has two arms, each four kilometres long) as well as ground vibrations owing to waves on the sea many miles away. Also, the solid materials of the supports for the mirror emit very weak 'creaks' and 'groans' owing to their thermal behaviour.

Prof Andrew Steane



Left: Results of the LIGO experiments: BP Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), *Phys. Rev. Lett.* 116, 061102 (2016), doi http://dx.doi.org/10.1103/PhysRevLett.116.061102. The top graphs show the observed strain at the two instruments, the middle graphs show the best fit prediction from numerical modelling, and at the bottom is the data again, analysed as a frequency spectrum versus time.

WWW.LIGO.ORG/MULTIMEDIA/GALLERY/LHO.PHP

WWW.LIGO.ORG/MULTIMEDIA/GALLERY/LLO.PHP

Top: Aerial view of LIGO Hanford Observatory (LHO).

Bottom: Aerial view of LIGO Livingston Laboratory.

LIGO, September 14, 2015

How express this dazzling of the dark?
This pull and twist that wound the sheets
of time
And pulsed that taught fabric,
Inscribed its eye-blink cry,
Its pin-prick shout
That for a sudden breath
Outshone the universe?

Twin globules of sloping space,
Vacuum-cleaners of the vacuum,
Each slides and slips the gentlest
Swirling paths into its timely maw.
How feel and say what jagged edge is this?
Its massive daggered heart is folded down,
Inexorably collapsed, glutted on itself,
Drawing down the curled-up horizon
Where time runs in.

So two mercurial blobs
Insensibly embraced across the
Depths of space some eon time ago,
Began their friendless waltz
In automatic tune,
Curling weights of folded space
Falling to their given final gyre.

To these globs, empty of thought,
No forgiveness applies,
And so we forgive their insatiable hunger.
Harbingers of their own doom,
Their grace is mathematical.
Warping each other's space
In utter obliviousness,
They rush into their own vortex
In massive neither joy nor fear.

Then as each distends to swallow the other
Their sudden death is born,
Scratching its rising scream
Into the world's field,
Pitching into the foundations the
Three-solar gravity-quake that
Throbbed the surface of the dark.

How express the murmur of that sound
A billion years away?
The ant's tread upon the moth's wing
On the far side of an impossible moon?
The weight of pin-prick winter light in a
cold dawn?

How show the stillness of the hanging
Mirror, its poised mass,
The thunder of the laser light?
The vacuum strained one thousand
Billion billionth part
And shook the foundations of our thought.
A ripple in the mind
That said,
"Behold! Behold the void that sings!"
And to each human countenance
A smile of grace it brings.

Prof Andrew Steane[1]

1 With a line from Stevie Smith

The LIGO website is packed full of fascinating short videos explaining LIGO, gravitational waves and more: http://www.ligo.org/multimedia.php

Even after allowing for all this careful design and construction, I think most scientists would have been more cautious about the recent announcement except for a very striking and convincing fact. Not just one but two of these huge interferometer devices was made, at opposite ends of America, and BOTH showed the same signal (with just the right delay of 10 milliseconds for the signal to propagate between them at the speed of light). It is very unlikely that both suffered from the same spurious effect at the same time, so the most likely explanation is a wave that passed over both of them. And, given all the candidates (and, believe me, physicists think this through very carefully indeed) a gravitational wave is the most likely explanation.

The interferometer devices, collectively called LIGO, have been operational before now and not detected anything. Other devices have also been operating for decades, but because their sensitivity was not sufficient, and no large enough signals came along, nothing was previously seen. Therefore when, in December and January, there was a rumour in the physics community that a gravitational wave signal had been found, most of us assumed that it would be a small signal, only just big enough to distinguish from noise. We were happy for the possible news, but we assumed it would be only just credible enough to merit an announcement. However, when the announcement came, the news was marvellous. The signal was 'huge' (that is, much bigger than the background noise). It was staring you in the face! You couldn't miss it! Here it is, in the figure on page 10. This image will surely now enter into the annals of science. It will become one of the iconic images of physics.

COLLIDING BLACK HOLES

Given this wonderful signal, the people working on the project were not in any doubt that something had happened (ie not just a noisy 'blip'), but they needed time to carry out as many checks as they could think of to rule out other influences, and to determine what could be inferred from the signal. That is what they were doing between 14 September 2015 09:05:45 UTC when the signal arrived, and 21 January 2016 when they sent their data and interpretation to *Physical Review Letters* for publication.

It turns out that quite a lot can be determined from those ten or so oscillations. You have quite a lot to work with there: the basic frequency, and also the way the frequency changes over time, and the way the amplitude changes as the frequency does. I am not expert enough to know how to do the calculation (more specifically, how to program a computer to do it) but I am willing to trust that it has been done correctly. The conclusion is that two black holes spiralled around and into each other, throwing off about three Suns'-worth of mass-energy in the form of gravitational waves as they did so. The dynamics of the signal imply that the black holes had masses of about 36 and 29 solar masses respectively. The distance away from Earth at which this event happened can also be inferred from the amplitude of the signal. The letter reports 410 mega-parsecs (a billion light years). The nearest galaxies to our own are at a distance a thousand times smaller than this, so we may infer that the event occurred a long time ago in a galaxy far, far away.

COMMUNAL CREATIVITY

I am thrilled that so much can be determined from this event, and indeed more will come as further analyses are done. I am also encouraged that all the painstaking efforts taken by a large number of people should have been rewarded in this way. It is like a smile coming from the cosmos; a good news story that we need in these troubling times of political unrest.

It so happens that in the weeks leading up to this announcement, I was myself learning about the LIGO instruments because I needed to understand how scientific experiments can be protected from seismic noise, and I knew that LIGO had the best protection currently known. Many humble researchers in laboratories across Europe, Australia and America have tested out ideas and built test rigs and performed numerical calculations to get the systems to the required level of stability. Most of their names will never be widely known. They are like the builders that put the stones into the cathedrals of Europe in the medieval period. They contributed to a larger project that represents the creative efforts of a community.

The scientific team chose *Physical Review Letters* as the place of their publication. This is an affirmation by them of the editorial standards of that journal. I also found it note worthy and heartening that the editors, and the American Physical Society, chose to make the paper immediately freely available to everyone. This was their way of extending an open hand to all people everywhere who take an interest in science. For this moment, questions of money were set aside.

And for this reason, this is also the moment just to celebrate the science for what it is. I will not be drawing any further lessons. I am very happy that, in some parts of the world at least, science, and the collaboration that it requires, can prosper in peace, and I salute all the skilled and careful people who brought this ambitious project to birth. ■

LHO End X station

WWW.LIGO.ORG/MULTIMEDIA/GALLERY/LHO.PHP

NOTES FROM THE HEAD OF PHYSICS

Prof John Wheater, Head of Department

DIGGING DEEP

As you can see from the photograph, the construction of the Beecroft Building continues apace. The piling rig has departed, having inserted no fewer than 223 reinforced concrete piles each 20m deep, and the site has been dug out to a depth of 5m. The gravel that has been removed is of good quality and is being used to landscape the Radcliffe Observatory Quarter site (what used to be the Radcliffe Infirmary in bygone days). At this point, if one continued digging, the walls of the hole would fall in – and, indeed, the Lindemann Building would fall into the hole. Often this problem is dealt with by using enormous temporary hydraulic props to take the strain until the floor plates are in place, but this would be very obstructive on our constrained site. So, instead, a system of ground anchors is being installed: these are 23m long pieces of steel that are inserted through the pile wall and literally pin it to the surrounding ground. Once that is done, digging will continue, eventually to a depth of 16m, and, if all goes well, by the time of the next Newsletter the contractors will be working their way back up as the lower levels are constructed.

NOBELS AND BREAKTHROUGHS

Just after the last Newsletter went to press, we learned that the 2015 Nobel Prize for Physics had been awarded for the discovery of neutrino oscillations. One of the recipients was Arthur B MacDonald, spokesperson for the SNO (Sudbury Neutrino Observatory) collaboration. Oxford, led at various times by Steve Biller, Nick Jelley and Dave Wark, played a leading role in SNO and great credit is due to them, their post-docs and students, and the Physics Workshops. Nobel Prizes, being essentially a nineteenth century conception, are only given to individuals but a few weeks later the Breakthrough Prize was awarded for the same discovery to the experimental collaborations so this time everyone shared in the prize, including Giles Barr and Alfons Weber who lead the Oxford group in T2K, another of the collaborations honoured.

The headline physics discovery of the past few months has been the detection of gravitational waves by the LIGO collaboration who have essentially constructed the most sensitive interferometer ever – in fact two of them. You can read more about it in Prof Andrew Steane's article (page 10). Here I'd just like to make a few observations. Firstly, that LIGO is not an Oxford experiment but that doesn't prevent everyone in the department being thrilled by its success. Secondly, that seeing something and understanding what you are seeing are not the same thing; frequently detailed theoretical calculations are crucial to the interpretation of data – that is certainly the case for LIGO, and Philip Podsiadlowski and colleagues in Bonn have made fascinating calculations of the merger of massive black holes. Finally, that the direct observation of gravitational waves represents not only a culmination of almost exactly a century of effort since Einstein published his theory of General Relativity, but also the beginning of a new era in which we will have an extra probe to study the cosmos.

FUNDING GRADUATE STUDENTS

As ever with new opportunities in science, it is the young who will in due course be able to take full advantage of them. Graduate students come to learn how to be independent researchers in areas of science that often appear bewilderingly complex at first sight. They do that through being supervised by the senior faculty but also from working with each other – even theoretical physics these days is very much a collaborative venture. We offer the most able students the opportunity to start their scientific careers in one of the world's best Physics departments. What is not so easy to see at first glance is the extent to which our graduate students actually contribute very significantly to the research that we do, in terms of ideas and insights as well as in overcoming the technical challenges. In fact, about 50%, which is a very high proportion, of our DPhil students carry on to post-doctoral scientist appointments at major universities all over the world, and a significant number ultimately become senior academics themselves. It is also notable that many people who start as graduate students in physics subsequently move out into many other areas of science and technology, taking their physics training and ways of thinking with them, and make contributions to society that no central planner would ever have imagined. Ensuring that we educate enough independently minded bright young people as physicists at graduate level is crucially important to the future vibrancy of basic research and to the wellbeing of economies around the world. As a result of the challenging funding landscape, we have found ourselves in a position where we have to reject a large number of excellent applicants every year. That is why we aim to build a substantial independent fund to support the doctoral studies of future generations. ■

WHY STRING THEORY?

OXFORD PROFESSOR AUTHORS POPULAR BOOK

If you type 'String theory is' into google, the first three words it suggests are 'wrong', 'dead' and 'bull****'. For a set of ideas best known as a candidate theory of quantum gravity, this represents a surprising amount of passion – and a tribute to the culture of our society that people care so much about the truthfulness of fundamental theories of nature.

STRING THEORY THEN

What actually is string theory? It refers to a set of ideas that are now almost 50 years old. They originate in the summer of 1968, when the Italian physicist Gabriele Veneziano wrote down an equation that appeared to describe certain properties of the strong interactions. This 'Veneziano amplitude' was a description of the interaction of pion particles to make one pion and one omega particle. It was a short, neat formula that appeared to describe the strong interactions – but what had it to do with strings?

Although today Veneziano's paper is viewed as the start of string theory, at the time – and for the next five years – it was a potential description of the strong force. Indeed, it was not until after three years of intensive work on the implications of this formula that a connection was made to strings – the particles described by Veneziano's formula could also be interpreted as the harmonics of an oscillating string, and his formula was revealed as one aspect of the consistent theory of quantum, relativistic strings.

> If you want to get rich in a gold rush, it is easier to do so by selling spades and panning equipment than by finding an enormous nugget.

Were oscillating relativistic strings a correct description of the strong force? The answer was no. Starting in 1973, it was realised with ever more detail that the strong force was actually described by quantum chromodynamics (QCD) – and not relativistic strings.

After five years of activity, string theory then disappeared into the backwaters of theoretical physics, re-emerging through a series of twists and turns as a potential theory of quantum gravity in 1984. Since then it has been a mainstay of thought in theoretical high-energy physics – but why do so many people work on a topic without direct experimental support? Almost fifty years after it first arose, we still do not know whether string theory is a correct theory of nature.

What even is string theory? The most basic definition is as the consistent theory of quantum mechanical, relativistic strings – and everything entailed by this. The subject has evolved to contain branes – extended, higher-dimensional objects – as well as strings, and also other ideas that were never suspected in the 1970s. However, these are not addenda, but logical consequences of equations first written down 40 years ago. One of these logical consequences is that the interactions of closed loops of strings behave in a similar fashion to the interactions of gravitons – a fact which lies behind the relevance of string theory to quantum gravity.

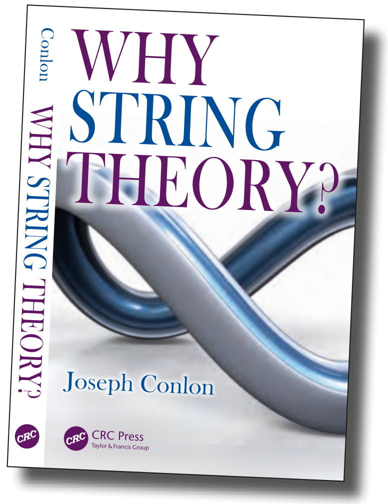
STRING THEORY NOW

Why is string theory popular? One of the main reasons for the widespread attraction of string theory within theoretical particle physics is the fact that it has provided tools and insights that go far beyond quantum gravity and the particular issues associated with quantum gravity. Caring about quantum gravity has been a good reason to work on string theory – but by no means the only reason.

This is reflected in the work on string theory carried out in Oxford, both in the Rudolf Peierls Centre for Theoretical Physics and also at the Andrew Wiles Mathematics Institute – there is an intellectual continuity that straddles the two locations. In the Rudolf Peierls Centre, Andre Lukas, Andrei Starinets and Joseph Conlon all work on string theory. Starinets is best known for his work on the hot relativistic fireballs produced when two large nuclei are collided, and for showing that these can be described using the equations of five-dimensional black holes. Lukas works on constructing the extra-dimensional geometries necessary for a ten-dimensional string theory to give rise in four dimensions to the observed spectrum of Standard Model particles. Conlon uses astrophysical X-ray observations to search for, and constrain, axion-like particles, a type of particle that arises generally within string theory. While all use string theory, the directly quantum aspects of the gravitational force is often present only as an elusive scent in the background.

The enduring popularity of string theory in theoretical physics is in part due to its appeal as a quantum theory of the gravitational force. However, it is also far more than this. Its ability to provide novel insights far away from its home territory has put it into the toolbox of many; the same intellectual fertility has also convinced many of its value in quantum gravity. While it does not logically have to be the case that a theory of quantum gravity should also enlighten many parts of mathematics and theoretical physics away from quantum gravity, it seems appropriate that it should. ■

Prof Joseph Conlon



- Provides the only modern, popular science account of string theory accessible to a general audience
- Covers a wide range of contemporary physics and mathematics
- Describes the big picture of known physics
- Addresses applications and criticisms of string theory
- Includes references for readers who would like to research the subject further

WAS THIS A WORLD FIRST?

A BELATED 'VIEW' OF LIQUID HE^3

The basic cryostat for low temperature (<4.2 K) experiments in current use is the He^3 Dilution Refrigerator, an instrument which has a fixed and sealed charge of He^3/He^4 gas mixture in addition to a conventional He^4 reservoir. Back in the 1960s He^3 cost about £70 per litre of gas at STP; in contrast, the current figure is of order 50 times higher. This once acceptable cost encouraged many research groups to design and construct He^3 cooled cryostats, and many could be found in the Clarendon Laboratory; specifically these were located in the research groups of Cooke (heat capacity), Hill (heat capacity), Mendelssohn (thermal conductivity), Rosenberg (thermal conductivity) and Wilks (properties of liquid and solid helium). The usefulness of liquid He^3 is marginal; He^4 boils at 4.2 K (enabling 1 K to be easily obtained by pumping) whereas He^3 boils at 3.2 K (enabling 0.3 K to be reached). However, on the absolute temperature scale this is a significant reduction of a factor three. The He^3 cryostats mentioned above were carefully constructed to have a bath of He^3 surrounded by pumped He^4, He^4 at 4.2 K and possibly two stages of insulation provided by liquid H_2 (20.4 K) and/or liquid N_2 (77 K). My own contribution was to construct a simple liquid He^3 stage that could be inserted into a standard He^4 dewar whose temperature could be reduced to 1.4 K. This particular arrangement was to enable measurements of magnetic moment and magnetic susceptibility of rare earth compounds to be made at temperatures down to ~ 0.5 K and in magnetic fields of 9 T. The temperature of 0.5 K may at first sight seem higher than expected, but this was caused by the extra heat influx arising from the movement of the sample between pick up coils in the low temperature environment. This simple construction enabled measurements to be taken at minimal cost and samples could be changed through a load lock arrangement even while the low temperature environment remained at ~ 0.5 K.

> The late Mike Leask, in his usual adventurous way, posited that we should try some optical absorption experiments at He^3 temperatures

A CHALLENGE TO THE EXPERIMENTALIST

In the wake of these experiments, which utilized a portable gas handling manifold and about 3 litres of He^3 gas, the late Mike Leask, in his usual adventurous way, posited that we should try some optical absorption experiments at He^3 temperatures! This would necessitate constructing the complete tail section of the He^4 dewar and the He^3 insert of glass with all the obvious risks, amplified by the fact that the He^3 glass insert assembly had to be manually lowered into the liquid He^4 bath of the main dewar.

Mike Wells, St Catherine's College 1967

Undaunted, we modified one of Mike's glass tailed cryostats to incorporate a double-walled insert, also made of glass within the dimensional restraints of a maximum diameter of 30 mm. The double wall was to provide thermal insulation between the He^4 (pumped to 1.4 K) and the liquid He^3. The questions in both our minds were (a) if the glass should fracture then the group's supply of He^3 would be lost in seconds and (b) what temperature might be achieved, given that an intense beam of white light was focussed on the sample of interest ($DyVO_4$). The experiment worked well and a lowest temperature of ~ 0.7 K was achieved; the temperature was determined by a measurement of the vapour pressure of the He^3 liquid with many attendant inaccuracies. However, and more exciting to both of us, we actually saw the liquid He^3 – for us the first and only time. In the cold light of morning we reflected on the possibility that we might have achieved a world first! Should we ask for a blue plaque to be erected on the wall of room 042?

WORKING ON WEEKENDS

Sadly, the experiment was never written up, it may have got a mention in the DPhil thesis of Janet Lowry (née Battison) who was in attendance on that particular Saturday (are all the best experiments carried out at weekends?) We were quite philosophical about the risk of losing some £300 of group funds (about a year's allowance of consumables at the time), but to contemplate repeating the experiment at today's prices would be foolhardy. As an aside, I am able to confirm that liquid He^3 (~ 3 ccs) is colourless. If anyone knows of a similar or recorded experiment, the author would be pleased to hear. ■

DPhil student Jordan Thompson, who is researching quantum magnetism, has revived this 30 year-old fridge and it is now being used for very low temperature heat capacity experiments under Prof Radu Coldea.

For more details of current work with Quantum Magnetism and Quantum Phase Transitions see: www.physics.ox.ac.uk/research/quantum-magnetism-and-quantum-phase-transitions

REMEMBERING **DICK DALITZ** (1925–2006)

On 11 February, the Rudolf Peierls Centre for Theoretical Physics held a special seminar in memory of Richard H Dalitz who founded the Particle Theory Group more than 50 years ago. Dick passed away in 2006 and a memorial meeting was held then. The Centre now hosts the 'Dalitz Institute of Fundamental Physics' and we were fortunate to have a dozen members of the Dalitz family, including his wife Valda, present at its inauguration.

Two of Dick's distinguished ex-students spoke about his scientific legacy. First up was Frank Close (DPhil 1969) who spoke about the famous 'Dalitz plot' introduced in 1953 which proved to be a valuable tool for studying the dynamics of 3-body decays, especially of the new 'mesons' and other resonances being then discovered in both cosmic rays and the first particle accelerators. Frank described how this led on to the proposal by Murray Gell-Mann of the 'Eightfold Way' for classifying the new particles and the quark model for the fundamental structure of matter. The next speaker was Prof Sir Chris Llewellyn-Smith (DPhil 1967) who took the story further and also provided a brief scientific biography (drawn from an article co-authored with Ian Aitchison which is to appear in *Biographical Memoirs of the Royal Society*). He discussed Dick's thesis work on 'Dalitz pairs' and his resolution of the 'τ–θ' puzzle in kaon decays which led on to the profound realisation that parity is *not* respected by the weak interactions.

After the talks, at a reception in the Dalitz Institute, Valda ceremoniously 'unveiled' a Dalitz plot (signed on the back by several Nobel laureates) which she kindly donated to the Particle Theory Group. Among the many alumni and well-wishers present were other ex-students of Dick (eg Ron Horgan, Professor of Theoretical & Mathematical Physics at Cambridge) and contemporaries such as Don Perkins, emeritus Professor of Experimental Particle Physics at Oxford. It was truly an occasion to remind us all why we really do what we do. ■

*For more information go to **www-thphys.physics.ox.ac.uk/people/SubirSarkar/DalitzFest.pdf** and **http://www-thphys.physics.ox.ac.uk/people/SubirSarkar/dalitzmeeting.html***

Left: Valda Dalitz at the event; Above: Dick's notes on a seminar by Frank Close.

Both talks were enlivened with personal reminiscences and are available online at http://podcasts.ox.ac.uk/dalitzfest especially for the many alumni who could not come to the event.

FORTHCOMING ALUMNI EVENTS

The department offers a series of special lectures, events and other opportunities for alumni to engage and stay connected. The most up to date information and details can be found on the website at **www.physics.ox.ac.uk/events**.

LEAVERS' RECEPTION

2 June, Oxford This is a special celebration for all third and fourth year students who will be leaving us. An informal lunch and a chance to collect their alumni cards, take a group photo and learn about the Careers Service and Internships.

PARTICLE PHYSICS EVENT – NEUTRINOS (TBC)

July, Canada House, London Please check the website for more information.

PHYSICS ALUMNI GARDEN PARTY

18 June, St Hugh's College (Maplethorpe Hall), Oxford Hosted by Prof John Wheater, Head of Department, and Prof David Marshall, Head of AOPP. Lecture by Prof Marshall plus other activities for all the family to enjoy in the beautiful gardens of St Hugh's College.

UNIVERSITY OF OXFORD ALUMNI WEEKEND

16 and 17 September, Denys Wilkinson Building, Oxford Friday night will feature telescope tours. On Saturday there will be lectures by Prof Andrew Steane on 'The first detection of gravitational waves' and by Prof John Wheater on 'Physics in 2016, what's new?'. These will be followed by a reception.

If you are interested in these events, please visit **www.physics.ox.ac.uk/events** or contact **alumni@physics.ox.ac.uk**. All these events are free, but we have limited capacity so tickets will go on a first come, first served basis. To avoid disappointment, visit our website regularly for updates.

DEPARTMENT NEWS & EVENTS

OXFORD CELEBRATES ROLE IN 2015 NOBEL PRIZE FOR PHYSICS

By Ian Shipsey

Nobel Banquet, Chapel Hall, Mansfield College. Front Row (L-R): Prof Amanda Cooper-Sarkar, Prof Ian Shipsey, Prof Don Perkins, Prof Steve Biller*, Prof Art MacDonald, Lady Helena Kennedy (Principal of Mansfield), Prof Nick Jelley*, Prof Roger Cashmore, Prof Dave Wark*. (* UK co-spokesperson/former co-spokesperson of SNO.)

On 14 December 2015, four days after the Nobel Prize was presented to Art MacDonald and Takaaki Kajita in Stockholm, the Particle Physics sub-department hosted a 'Nobel Banquet' to celebrate with Art the award of the 2015 Nobel Prize and 2016 Breakthrough Prize. Members of the department, alumni, friends, and former members of the Sudbury Neutrino Observatory (SNO) collaboration, many of whom had not seen each other in years, joined the celebration. Art, who is Spokesperson of SNO, was made an Honorary Fellow of Mansfield College and gave a captivating speech in which he recounted the many year journey from conception of the experiment to design, construction, commissioning and data analysis that ultimately led to the evidence that neutrinos oscillate from one flavour to another and therefore have mass. Oxford was the only UK university in SNO. Art noted the major contributions made by Oxford students, post docs, staff and academics in all aspects of the experiment, including members of the Oxford mechanical workshop, who played a key role in constructing the acrylic vessel central to the SNO experiment.

Roger Cowley (1939–2015) – A Passing Note

With a feeling of joyful reflection members of Oxford Physics, Fellows of Wadham College, family and friends gathered last September for a celebration of the life and work of Roger Cowley. Sadly, Roger died last January following a difficult year as a result of a cycling accident. Roger was elected to the posts of Dr Lee's Professor of Experimental Philosophy, Chairman of Physics and Fellow of Wadham College during his time in Oxford. He was also an inspirational teacher to a myriad of undergraduate and graduate students at Cambridge, Edinburgh and Oxford.

In contrast to the usual memorial service, it was his wife Sheila's wish that the event should be celebratory in keeping with and to reflect Roger's dedication to physics and to family life. Therefore a programme of events was compiled to bring together colleagues from far afield who represented Roger's work initially in Cambridge, followed by prolonged stays in Chalk River (Canada), Edinburgh and finally Oxford. His research work using both neutrons and X-rays took him to many European research establishments including the ISIS and ILL neutron sources and the Diamond and ESRF light sources. In each of these establishments Roger made many friends as a result of his persuasive way of getting colleagues and students to appreciate his keenly contested ideas; he made it appear as if the concepts were one's own and he was merely supporting them! His competitive abilities translated directly onto the tennis or badminton court and his croquet skills were legendary to those who dared to compete with him.

The morning session, held in the Denys Wilkinson Building contained short talks and reminiscences by past colleagues and graduate students. This included recollections of Roger's work on early triple axis spectrometers, work with liquid helium and anharmonic phonons, collaborations at ISIS and work on thin rare-earth films at Oxford and the on-going saga of UO_2. The session was ably choreographed by Bill Stirling, Roger's first postgraduate student. This was followed by lunch in Wadham College and the highlight of the day, an afternoon concert in the Holywell Music Rooms by the Adderbury Ensemble. The concert delightfully reflected Roger's love of music and in particular his appreciation of the work of Shostakovich.

My own affection for Roger over many years was that of a novice learning from a teacher who could portray the most difficult of problems in the easiest of terms, complete with a smile, sincerity and a wry sense of humour (often accompanied by a twiddle of his tie). I join all those who attended in expressing our collective appreciation of the contributions made by Oxford Physics, Wadham College and Roger's family to this sad but happy memorial event.

Mike Wells, St Catherine's College 1967

KEY STAGE 3 PHYSICS CHALLENGE DAY: LIGHT, LASERS AND OPTICS

'The motivation behind this event is to provide the opportunity for Year 9 students to discover new areas of physics, delve deeper into topics already taught, and provide more hands-on experiments where cost prohibits students from accessing the equipment needed.'

Dr Katherine Richard, Head of Physics at St Edward's School and Oxford Partnership Coordinator

90 STUDENTS

NINE SCHOOLS IN OXFORDSHIRE

'It was interesting and enjoyable'

'I liked the hands-on and interactive approach and the friendly facilitators'

Participating students

In January, 90 students from nine schools in Oxfordshire visited the University to complete a series of challenges on the theme of light, lasers and optics. The students, aged 11–14, worked in small teams on practical activities which were facilitated by more than 15 physics DPhil students. Prizes were awarded to the top three teams. The event was hosted in the Department of Education; Dr Judith Hillier, a lecturer in science education (physics), explained why the event is so important: 'Being selected to go on a science trip in the early years of secondary school can be key in cementing a young person's belief that science is for them, and that they have the potential to succeed – at GCSE, A-level and beyond.'

The day consisted of three hour-long workshops on the topics of lasers, optics and light. The laser workshop included various practical puzzles using a low power laser, beam splitter and mirrors (from a strategy game called Khet). In the optics workshop, students built their own telescope in order to read a secret message on an opposite window, and sketched the optical path of light through the telescope. In the light (electromagnetic spectrum) workshop, students enjoyed a carousal of activities based on different bands of the electromagnetic spectrum. They used a kitchen microwave to calculate the speed of light by removing the rotating plate and measuring the distance between melted spots, caused by the standing waves, in a layer of cheese. This inspired lots of interesting discussion.

'The event had an impact on my students, they all want to be in the Triple Science group as they can now see where it can take them. One student in particular benefited from the experience as he now wants to look at a science career and he wants to do well so he can attend other events…he now sees science as his favourite subject.'

Rachel Harris, teacher at St Birinus School

One of the most popular activities of the day was exploring infrared radiation with an infrared camera: the students were clearly engaged and frequently asked 'how much does one of these cost?' and 'where can you buy one?'

The Key Stage 3 Challenge Day was developed by the Oxford Schools Science Partnership, along with a series of other events for students and teachers, with financial and practical support from The Ogden Trust. The partnership consists of the Department of Physics and Department of Education at the University and a number of local schools. The Oxford Partnership Coordinator is Oxford Physics alumna Dr Katherine Richard, who is now Head of Physics at St Edward's School. The event is in keeping with the new departmental School Outreach Strategy to work more closely with younger students from local schools while continuing our national access activities.

© KATHERINE RICHARD

© KATHERINE RICHARD

The Key Stage 3 Challenge Day has been running for four years with a rotation of three different themes. The next event will explore magnetism: please contact **schools.liaison@physics.ox.ac.uk** if you are interested in being involved or finding out more about the outreach programme at Oxford Physics.

FIVE MINUTES WITH...GEOFF STANLEY

DPhil student in Atmospheric, Oceanic, and Planetary Physics

Tell us a bit about your background…

I'm a DPhil student in Atmospheric, Oceanic and Planetary Physics. I got here by way of an MSc in Physical Oceanography at U Victoria (Canada) and an undergrad in Pure & Applied Maths at U Waterloo (Canada). Now you may correctly guess that I'm Canadian. I grew up in quasi-rural Ontario, amongst lots of trees and relatively far from other humans.

When/how did you decide to become a physicist?

In elementary school we did a project my teacher called 'The Project of Awe', the idea being to research some thing that awed you – it could have been anything. Being suitably influenced by my environmentally-minded parents, I read *The Sixth Extinction: Patterns of Life and the Future of Humankind* by Richard Leakey and Roger Lewin. I would trace my decision to become a physicist back to this Project of Awe, because it was that which embedded climate change as my driving motivator, and without deciding what type of physicist I wanted to be – a climate physicist, or close enough – I may have strayed.

Why do you think it is important to study physics?

I study physics because it enables us to (attempt to) predict the future – specifically the future climate. By those predictions it enables us to prepare for changes to come, whether that be by emitting less carbon or by adapting our infrastructure and food systems to harsher conditions.

Can you explain the work you do?

I study the dynamics of the world's largest ocean current, which encircles Antarctica, called the Antarctic Circumpolar Current (ACC). This strong eastward flowing current is a barrier to southward heat transport, effectively keeping Antarctica cold. Also, the densest waters in the ocean are formed at the surface off Antarctica's coasts, so the ACC in part controls the heat and carbon storage of the deep ocean. Any changes in the ACC spell potentially massive changes in Earth's climate. Under anthropogenic climate change, it is widely expected that the southern hemisphere westerly winds, which drive the ACC, will intensify and shift southwards. Will the ACC follow, or do topographic barriers such as Kerguelen Plateau, southeast of Africa, keep it north? Is there a tipping point, wherein a marginally further southward shift of the westerlies causes a jump of the ACC across Kerguelen? The answers to these sorts of questions are hidden within the deceptively complicated Navier-Stokes equations. I try to boil these equations down to simpler forms that still capture the ACC's key features, yet allow us to understand how the wind and topography interact to determine the ACC's trajectory.

What are the current challenges in this field?

The astronomical disparity between scales of oceanic flow. We have a 'thermohaline circulation' spanning tens of thousands of kilometres, and turbulence occurring at the millimetre scale, and the latter directly drives the former. Numerically simulating all these scales is simply impossible. Since there will always be smaller, unresolved, and mysterious scales of motion, one of the best things we can do is to observe the real ocean. While models will inevitably get better with computer power, observations taken now are as useful to us now as they will be to climate scientists in 50 or 100 years. Securing funding for long-term ocean observing systems remains a major challenge.

What other interests do you have besides physics?

If a genie whisked me back to age 18 and told me I could not study physics or climate, I might have studied human physiology, biomechanics or nutrition. In some respects I would eagerly use myself as a test subject! What began as a summer adventure to cycle across Canada has led me to be an aspiring endurance athlete. I've cycled and camped up and down the west coast of USA, and raced myself from Toronto to Montreal, across Wales, and from Oxford to Paris. Recently I've lost the wheels, studied running form, and raced up to 67 miles by foot in a day. It continues to amaze me what the human body is capable of when, after ten or more hours of continual effort, it finds harmony with the mind and reaches some deeper, more efficient, seemingly limitless state. Can I take something of this harmony out of the realm of endurance sports and into my daily working life? I'm aiming to find out. And of course, half the joy of all this lies in being in the great outdoors.

What scientific breakthrough would you like to see in your lifetime?

Aside from a fuller understanding of Earth's climate and how it will change, I would love to be alive when humans generate electricity from nuclear fusion. I would not, however, rely on this as a solution to climate change, because we do not know how far away this is feasibly, and the practical transition of infrastructure in hundreds of different countries is bound to be slow. For a second take of the question, I'd like to see a breakthrough in the scientific community wherein we video-conference more and fly less.

What are your plans in the future?

I'd like to run a sub-three-hour marathon, tend an intensive organic garden, appreciate at least one sunrise and sunset per week, move around the world not too many more times but each time cultivating a close-knit community of friends, thinkers and change-makers, and settle down in a beautiful place where mountains meet the ocean and bicycles are the norm. I hope I am lucky enough to have the opportunity to continue researching climate physics. And someday before I die I'd love to fly a self-powered aircraft. ■

RRS Discovery III

WWW.MARITIMEJOURNAL.COM/__DATA/ASSETS/IMAGE/0032/51379/MJOCT13DELG-FERRI.JPG

© JOHN CAIRNS

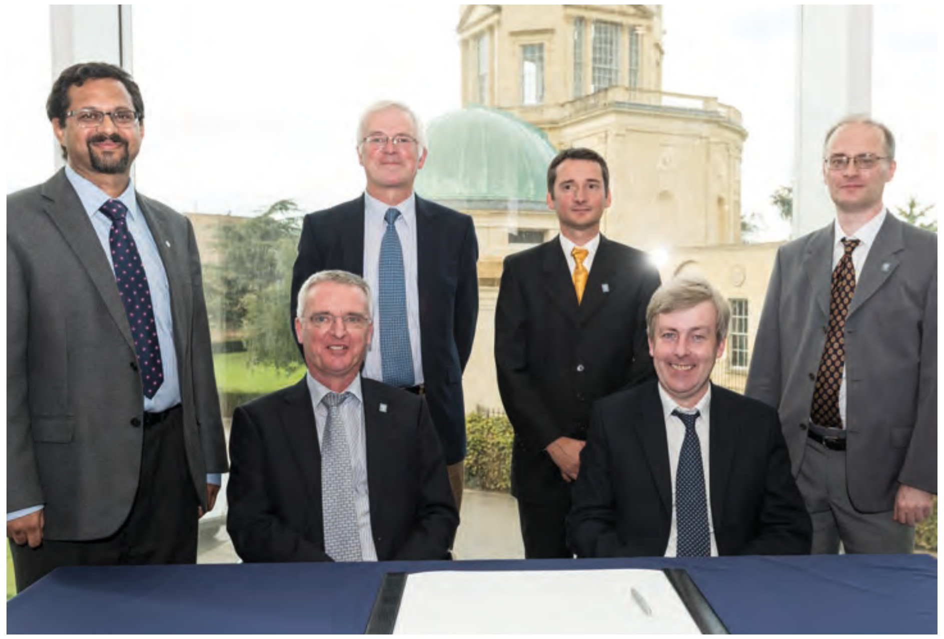
Above and right: Alumni enjoying the events.

The eighth **SATURDAY MORNING OF THEORETICAL PHYSICS** took place on 19 September 2015. Talks by Prof John Wheater, Prof James Binney and Prof Pedro Ferreira discussed 'Einstein's General Theory of Relativity a Century On'. For more information see https://saturdaytheory.physics.ox.ac.uk.

This was followed by **MEETING MINDS: OXFORD ALUMNI WEEKEND**, which started with a lecture by Dr Allan Chapman on 'Robert Hooke's Micrographia: Light, Lunar Geology, and Aeronautics'. Prof John Wheater then sprang into action again, and together with Prof Ian Shipsey spoke on 'From Quark to the Cosmos'. This was followed by a reception, telescope tours and hands-on demonstrations including space instruments and lasers. We look forward to seeing you all in September 2016 for the next Alumni Weekend.

© JOHN CAIRNS

Right: Prof Ian Shipsey in action.



HARMONI is the first light, adaptive optics assisted, spectrograph for the European Extremely Large Telescope (E-ELT), providing integral field spectroscopy with unprecedented spatial resolution at visible and near infrared wavelengths. A work-horse instrument, HARMONI will carry out detailed observations of a wide range of astronomical sources, from exo-planets to distant galaxies. It will be designed and built by an international consortium led by a team of Oxford Physicists, with Prof Niranjan Thatte as Principal Investigator. The Science & Technologies Facilities Council (STFC) and the European Southern Observatory (ESO) directors signed the contract for the design and construction of HARMONI, at a hardware cost of £14.2 million, at a ceremony in Oxford on 22 September 2015.

Above left: Prof N Thatte (PI), Prof Tim de Zeeuw (ESO Director General), Ian Bryson (Project Manager), Dr Joel Vernet (ESO Project Scientist), Prof Grahame Blair (STFC Executive DIrector (Programmes)), and Dr Peter Hammersley (ESO Project Manager) at the signing of the agreement for the design and construction of HARMONI. Right: A LEGO model of the European Extremely Large Telescope (E-ELT).

PHYSICS ALUMNI LECTURE AND DRINKS RECEPTION

Oxford and Cambridge Club, London

11 March 2016

Prof David Wark discussed experiments seeking the elusive particles called neutrinos, including the major Oxford involvement in the SNO experiment (which was awarded the 2015 Nobel Prize in Physics as well as the 2016 Breakthrough Prize). Prof John Wheater and Dr James Dodd (Alumnus) hosted the evening.

PHYSICS CAROL SERVICE

21 December 2015

Jim Williamson organises this delightful occasion for alumni, family and friends in the University Church of St Mary the Virgin, followed by wine and mince pies. Any member of the department (including alumni) who would like to sing in the choir this year, and is not already on the list, should contact Jim Williamson: jim.williamson@physics.ox.ac.uk.

'NUCLEAR IS FOR LIFE, A CULTURAL REVOLUTION'

Lecture by Prof Wade Allison (Emeritus Professor of Physics and Fellow of Keble College),

11 December 2015

The lecture aimed to show that there is no reason why nuclear energy should not be the ideal source of carbon-free energy. Current radiation regulations are based on 70 years of social appeasement. Prof Allison suggests nuclear power should be freed from these science-blind restrictions and so help save the planet. His latest book and website provides more information on this hot topic. www.radiationandreason.com

CLIMATE CHANGE IN THE RUN-UP TO THE PARIS CONFERENCE: WHAT HAS PHYSICS GOT TO SAY?

Royal Society, London, 6 November 2015

This was a fantastic opportunity to meet some of the current Oxford faculty in Atmospheric, Oceanic and Planetary Physics who are engaged in the research that underpins the debate over climate change – and discuss some physicists' ideas of what we should be doing about it. We will be hosting another event like this in the autumn.

You can see the climate change talks on the Alumni Blog here: www.physics.ox.ac.uk/blog/alumni

PHYSICS ALUMNI RECEPTION

2 October 2015, London

Alumnus Dr Richard Golding kindly opened the doors of his home to welcome fellow physics alumni to a fantastic evening of drinks and networking.

WOMEN IN STEM DAY

Beginning this year, 11 February will be recognised as a global celebration of equal participation and the accomplishments of female researchers across all aspects of science education, training, employment and decision-making processes.

ALUMNI STORIES

*We welcome stories from all alumni. Please email: **contact@physics.ox.ac.uk***

RICHARD JL SENIOR, CHRIST CHURCH, 1959

LIFE-CHANGING ADVICE

Most of my ancestors on my mother's side went to Worcester College so that was why I took the entrance exam in Physics there as well as at Christ Church. It was the first year after National Service had been abolished, so half of my freshman year was made up of men who had come out of the armed forces and the others were men like me who came up straight from school. Worcester offered me a place in 1960 but Christ Church offered me a place in 1959 so I accepted the House. In my last year my tutor asked me to stay on and do a DPhil in Physics, but I told him that I read physics because I thought it would be more practical than maths and I planned to go to the London School of Economics and go into business. He looked at me, horrified, and said 'Don't do that! Go to America and go to business school'. I asked him how I could do that and he confessed not to know but told me that the English Speaking Union did.

To cut a long story short, I ended up with a free ride at Yale for two years and a Fulbright Travel Grant to get me there and back. I met my American wife, Diana, at a picnic on the third day because the grass was cold and I was the only one to have brought a blanket. (Two marriages resulted from that blanket!) I'm one of the few people who have played cricket for Yale.

As a newly minted graduate with a master's in business, I had to return to England under the terms of my Fulbright. Diana and I were engaged by then and she, too, moved to London, where we were married a couple of years later. We'll celebrate our 50th this year.

My first job was with Tate and Lyle in their sugar refinery on the Thames in East London. I was the manager of the 'white end' which meant that I was responsible for packaging and shipping, with a team organised along military lines – I was a Lieutenant in the battalion. I played cricket for them too! After a couple of years there, McKinsey and Company got in touch and I started to work for them a few weeks after getting married.

McKinsey was an extraordinary experience. At age 26 I was the youngest consultant they had hired in London and yet I was working with the top management of household name organisations including BBC Radio. One senior manager asked me how old I was; I told him and he replied 'My son is your age and I certainly wouldn't take his advice'. Nevertheless, we got on well after that.

In the early 1970s, I led the team that reorganised the Welsh National Health Service and, after that, another team that reorganised the Eire National Health Service. That experience led to an avocation in health care, which continues unabated to this day.

BACK TO AMERICA

In 1972 Diana wanted to go back to Chicago with our two children; her parents and grandparents were not well. McKinsey transferred me to the Chicago office, where I discovered that we were not 'gods' as we were in London. A couple of years later, the President of Diana's now 129 year old family company retired and the family offered me the job for the coast-to-coast linen and uniform hire business. I accepted. I served a term as Chairman of the Board of one of the two industry associations and, a few years later, of the other one. They have now merged. I've spoken at conferences on four continents. We bought the company from Diana's family and I'm still the CEO but I kicked myself upstairs to Chairman 10 years ago and promoted one of my Vice-Presidents to President and Chief Operating Officer. I'm the longest serving outside director of a flower seed company with operations all over the world, including England. For four years I was Chairman of the Board of a private day school in Chicago and was heavily involved in the hiring of a new headmaster. My interest in healthcare led me to accept a board membership of Northwestern Hospital, the top academic medical center in Chicago. I'm now a Life-Trustee of the Foundation. ■

He looked at me, horrified, and said 'Don't do that! Go to America and go to business school'.

Above: Richard during his days in Oxford. Below: Christ Church.

WITH THANKS TO RALPH WILLIAMSON WWW.RALPHWILLIAMSON.CO.UK AND CHRIST CHURCH OXFORD

LIFE SCIENTIFIC OF ELSPETH GARMAN, LINACRE, 1976

*Interview with Elspeth Garman on BBC Radio 4's 'The Life Scientific' with Jim Al-Khalili can be found at: **http://www.bbc.co.uk/programmes/b04kbjhg***

I am 6½ and it is a special day. The desks in my primary school are cleared to the sides, and a large chalk circle has been drawn on the floor to represent the sun. The teacher has an orange speared by a knitting needle, and walks round the room rotating the orange on its axis. I am fascinated. That evening I carefully note the view from my bedroom window in our large, freezing Victorian vicarage, and then again in the morning. To my disappointment the view is unchanged – the earth has not rotated beneath us. I thus get the idea of relative motion...

I am 7 and I do my first experiment. My mother returns from the nearest town 20 miles away with a tube which produces red stripes on the outside of white toothpaste. I ask if the stripes are already on the paste inside or if they appear as the paste comes out. I get a non-committal 'adult' reply, so after dark I dissect the tube to find out. I make a big mess and get into trouble.

I am 11, I have failed the 11+ and am at a Church of England convent boarding school. The end of year exams are not going well. I am bottom of the class in most subjects, with only Algebra left to go: the 'B' stream beckons. Two 'friends' lock me in the school library for three hours as a joke. All I have for entertainment is my algebra exercise book, and it occurs to me that I could read through it: revision is not a practice I have previously contemplated. I come top in the exam with 87% and thus cling to my 'A' stream status and acquire a competitive urge.

I am 13. The class is travelling by bus to the senior school for a lab session. Our physics teacher, Sister Janet Elizabeth, asks how long it takes for light to travel from the sun to the earth. I shout 'eight minutes'. My classmates turn on me and ask how I can possibly know this, and I can't answer. I have somehow just always known, and now my destiny is set: I will study physics. From then on my nickname on good days is 'Prof', but never in my wildest dreams do I imagine that this will be apposite one day!

Elspeth receiving the Mildred Dresselhaus Guest Professorship in Hamburg, January 2016. Elspeth recently won the 2016 ACA Fankuchen Award (www.amercrystalassn.org/2016-award-winners) and the Mildred Dresselhaus Award 2015 (www.cui.uni-hamburg.de/en/2015/07/mildred-dresselhaus-awardees-2015-selected).

AN EXPERIENCE THAT CHANGED MY LIFE

I am 18 and have just failed the sixth form entrance exams to read Natural Sciences at Newnham College, Cambridge. I leave for nine months of teaching maths and science in a large girls' secondary school in Manzini, Swaziland. I cover every subject on the curriculum except Zulu. I discover I am born to teach. This experience changes my life and eventually results in the amazing gift of a Swazi foster daughter, the orphaned child of one of my pupils, now with three children of her own.

I am 20 and in my second year at Durham University reading physics. I spend 15 weeks at CERN in Geneva and join the team determining the magnetic moment of the muon. It is stimulating but tough. I realise that not many women go into nuclear physics research, but decide I will be one of them. The experiments involve lots of people, too many for me to understand every aspect of the data collection, so after Durham I go to Oxford to do a DPhil in experimental low energy nuclear physics. Here, with a small team, we plan and execute the whole experiment ourselves on the accelerators housed four floors under Keble road.

I am 24 and rowing for Osiris (the University's 2nd crew). During my DPhil and seven subsequent years as a research officer and college tutor in the Nuclear Physics Department, I teach physics at seven different Oxford colleges. Having married my landlord, Dr John Barnett, I want to stay in Oxford, but nuclear physics research funding is starting to dry up.

A CRAZY MOVE

I am 33 and am approached by Louise Johnson from the Laboratory of Molecular Biophysics (LMB), who asks 'What next?'. I don't want to think about this, since I now have a two year old daughter and am prime carer for my 81 year old mother-in-law. However, Louise persists, telling me the LMB is seeking someone to look after their new X-ray generator and nuclear physics electronic detector, with which they carry out protein crystallography, a technique used to find the three-dimensional shapes of biologically important macromolecules. Six weeks later I am working in LMB 66% time and have changed fields to protein crystallography/structural biology. I do not know what an amino acid or a protein is, and I have a lot to learn!

After 12 years of looking after the LMB X-ray equipment, and with a second daughter (now 8) at home, I start working full time and begin my own research group. I have been lucky enough to work with a continuous stream of great graduate students, and together we have made well-recognised contributions to methods development for structural biology (cryo-cooling techniques for crystals to extend their diffraction lifetime; elemental analysis of proteins using a nuclear physics proton accelerator; systematic studies on radiation damage-induced artefacts in protein crystallography). I have travelled the world teaching, demonstrating and lecturing these methods, and made many friends. In 2009 I look at my group: there are two Mexicans, a Russian, a Jordanian, an Indian postdoc and me. I love the international nature of our science and the cross-cultural exchange it fosters. In the same year I am seconded 50% time for five years to the Maths, Physics & Life Sciences Division's Doctoral Training Centre, as Director of first the Life Sciences Interface and then the Systems Biology Programmes: a wonderful interdisciplinary experience which has resulted in four outstanding graduate students joining my group.

I have not regretted my crazy move of research fields for a second. Macromolecular crystallography requires intellectual contributions from many different fields of science, and communication is a very useful skill. Despite now having a senior rail pass, I am still learning, and I feel fortunate to work with the next generation of inquisitive and enthusiastic young scientists. ■

COMINGS, GOINGS & AWARDS...

AWARDS

DR TESSA BAKER won the 'Women of the Future (WOF): Science' award. WOF recognises and nurtures young female talent in the UK, and celebrates women 'who have carved out a successful niche in their careers'.

PROF TONY BELL has been awarded the 2016 Eddington Medal by the Royal Astronomical Society for his work on the acceleration of energetic particles by shock fronts occurring in supernova blast waves, active galaxies, the solar wind and elsewhere in the universe.

PROF FELIX PARRA has been awarded the prize for the Best Young Theoretical Physicist by the Royal Physical Society of Spain and the BBVA Foundation.

DR RALPH SCHOENRICH has been awarded the 2016 Winton Capital Award by the Royal Astronomical Society for his studies of the Milky Way.

JEFF LIDGARD has been awarded Runner Up in the National Instruments Engineering Impact Awards (Education category) for his work modernising the Oxford Physics Teaching Labs.

PROF PETER READ has been awarded the Lewis Fry Richardson Medal of the European Geosciences Union. The medal is awarded for exceptional contributions to non-linear geosciences.

Careers Service

Did you know? The Careers Service is for life…not just during your time in Oxford!
Contact Dr Michael Moss (**michael.moss@careers.ox.ac.uk**) or visit **www.careers.ox.ac.uk** for more information.

2016 Breakthrough Prize

The 2016 Breakthrough Prize in Fundamental Physics has been awarded for the demonstration of neutrino mixing. The recipients include the **SNO (SUDBURY NEUTRINO OBSERVATORY)** and **T2K** collaborations, both of which have a substantial Oxford Physics component. Many congratulations to the Oxford SNO group, who made several seminal contributions to the SNO experiment. Oxford SNO has been led at various times by **PROF STEVE BILLER**, **PROF NICK JELLEY** and **PROF DAVE WARK**; great credit is due to them, their post-docs and students, and the workshops. Prof Dave Wark started the T2K project in the UK and **PROF GILES BARR** and **PROF ALFONS WEBER** have lead the Oxford T2K group from the beginning. Congratulations to them, and their post-docs, students, and technical staff. More details at **https://breakthroughprize.org/News**

Top to bottom: Steve Biller, Nick Jelley, David Wark, Giles Barr, Alfons Weber

PROF JUSTIN WARK, **DR SAM VINKO** and **DR ORLANDO CIRICOSTA** are the winners of the American Physical Society's Dawson Award for 2015 (formerly the Excellence in Plasma Physics Award) 'for creative and novel use of the hard X-ray free electron laser to isochorically create high density plasmas and accurately measure the ionization potential depression, and for new theory that addresses discrepancies with long standing models and provides stimulus for continued developments'.

L-R: Justin Wark, Sam Vinko, Orlando Ciricosta

The Physics Department has a presence on Facebook, Twitter, LinkedIn and Instagram. Join the conversation:

PhysicsOxford

@OxfordPhysics

OxfordPhysics

physics_oxford

FSC www.fsc.org MIX Paper from responsible sources FSC® C013002

PRINTED BY OXUNIPRINT ON FSC® CERTIFIED PAPER, USING VEGETABLE-BASED INKS. PRINT PRODUCTION SYSTEMS REGISTERED TO ISO 9001 & ISO 14001 STANDARDS

IMAGES © MEDIA SERVICES UNIT, DEPT. OF PHYSICS (UNLESS OTHERWISE INDICATED). COVER IMAGE: © EUROFUSION

DESIGN: CATHERINE CHARNOCK CREATIVE: WWW.CATHERINECHARNOCK.CO.UK

We hope you enjoyed reading this issue of the Physics Department's newsletter. To contact the newsletter editor, Prof Fabian Essler, please email **newsletter@physics.ox.ac.uk**. For latest news on developments at the Oxford Physics Department, see **www.physics.ox.ac.uk/about-us**. To contact the alumni office, email **alumni@physics.ox.ac.uk**.