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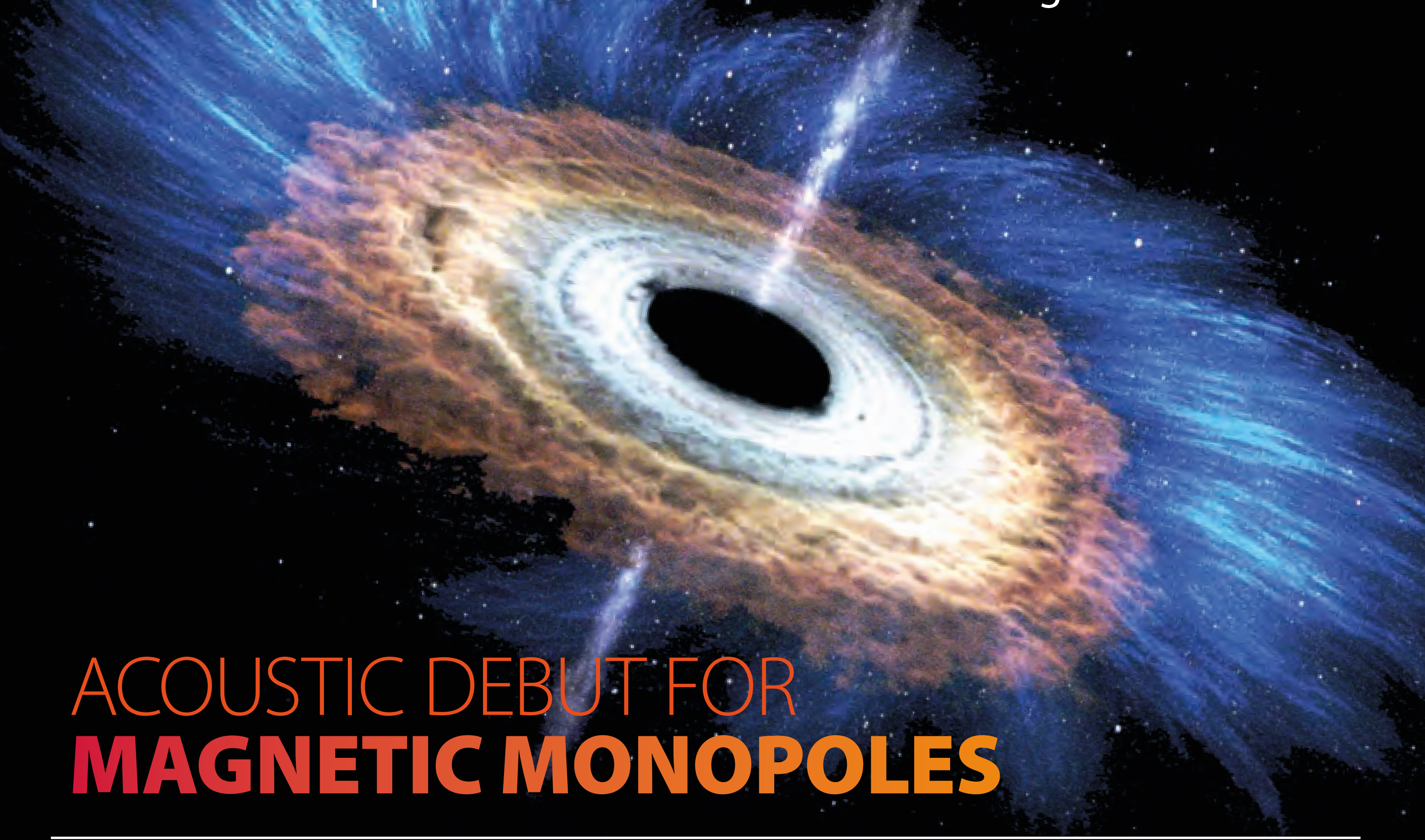
Department of Physics

Newsletter

UNIVERSITY OF OXFORD

A CENTURY OF BLACK HOLE PHYSICS

Oxford scientists have successfully modelled the destructive influence of a supermassive black hole on a wandering star



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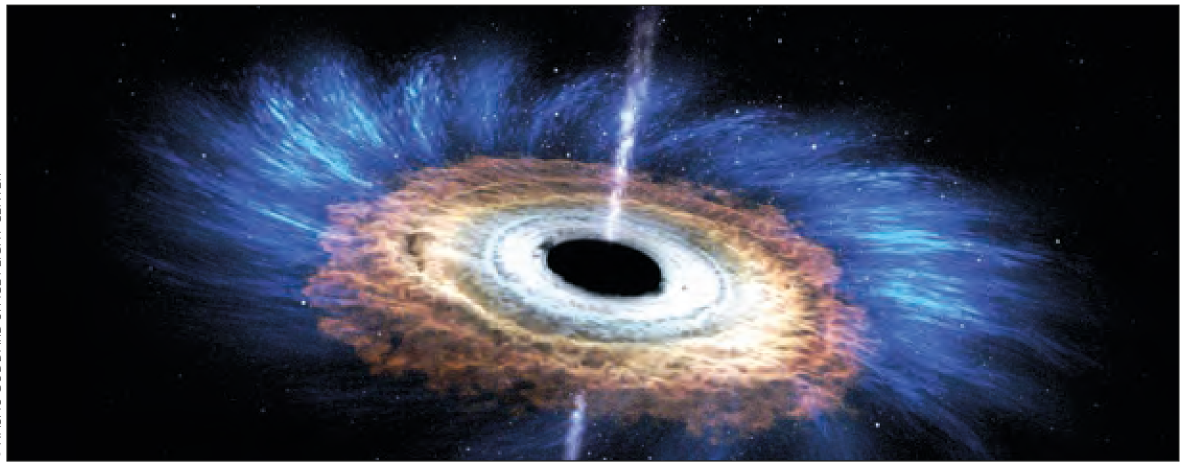
A CENTURY OF BLACK HOLE PHYSICS

Oxford scientists have successfully modelled the destructive influence of a supermassive black hole on a wandering star.



These are heady times for black hole astronomers. Recent years have marked a steady stream of observational triumphs for this field. Teams led by Reinhard Genzel (Max Planck Institute, Garching) and Andrea Ghez (UCLA) have revealed the fully resolved orbits of individual stars about the massive black hole at the centre of our Milky Way Galaxy. The LIGO (Laser Interferometer Gravitational-Wave Observatory) collaboration has borne fruit with the spectacular (now routine) direct detection of the gravitational radiation from merging black holes and neutron stars at cosmological distances. Finally, this year's astronomical show-stopping image of the event horizon environs of the black hole in the galaxy M87 captured everyone's attention. While the public was mesmerised by the gaping black void in the centre of illuminated surroundings, astronomers argued amongst themselves about what this barely resolved marvel of interferometric reconstruction was actually telling us.

It is hard to remember, but black holes used to be a topic that serious-minded physicists would shun – Einstein himself scoffed at them. Yet, within the career span of the author, black holes have tunnelled from physics anathema to grand unifier, a link uniting gravity with thermodynamics, particle creation and string theory. In common with all great physics, by uniting formally disparate fields, black hole theory introduces its own profound difficulties in the form of the 'information paradox'. The quest for understanding black holes drives much of the activity at the forefront of theoretical physics.

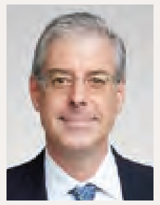
SEARCHING THE SKY FOR BLACK HOLES

The historical challenge for the astronomer wanting to find compelling evidence for a black hole has been to figure out how to detect what amounts to empty spacetime. If we play by the rules of classical physics, a black hole is just a vacuum solution to the field equation: move along please, nothing to see here. The quantum radiation that is emitted (first discovered by Stephen Hawking) is utterly unobservable from black holes in the mass range of interest. If, however, the black hole was part of a close binary system, gas from the normal star would be tidally drawn towards the hole. In this process of 'accretion', the gas would become very hot due to compression and turbulent heating. (A lot of physics is hidden in that statement!) It is this hot gas that the observational astronomer literally focusses upon. Black holes in binary star systems are copious sources of X-rays; ordinary stars can't possibly compete with them. This is the handle that observers like to use to find black holes.

BLACK HOLE ACCRETION DISCS

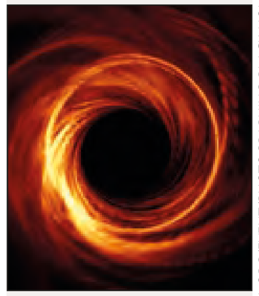
The gas near the black hole in a binary system is not simply falling headlong into a central void. The matter has orbital angular momentum, and angular momentum is conserved. An element of fluid cannot radiate away its angular momentum like so much heat; the process is much too inefficient. Rather, the fluid element must pass on its angular momentum to a neighbouring element a bit further out, which in turn passes it on to another nearby neighbour, and so forth. This process of transport is mediated by the formation of a coherent disc, a so-called accretion disc, in which gas on neighbouring circular orbits is mixed via turbulence. Turbulent mixing ultimately enables the angular momentum transfer to occur, heating the gas in the process, and if not quite lighting up the black hole, then certainly lighting up its neighbourhood.

The theory of accretion discs was developed by some of the most prominent astrophysical theorists of the 1970s: Nikolai Shakura, Rashid Sunyaev, Donald Lynden-Bell, James Pringle, and Martin Rees all played seminal roles. At a time when the existence of black holes was still a matter of controversy, the hope was that a robust theory of accretion would allow X-ray observations to reveal their presence. Alas, the theory of black hole accretion, replete with magnetohydrodynamical turbulence and relativistic jet-like outflows, turned out to be too complicated to be used as an unambiguous observational tool. Instead, the problem turned around: accretion discs emerged from this era as fascinating astronomical objects in their own right, worthy of their own field of study, much as we study the structure and evolution of stars. In the meantime, black holes have acquired such a vast and overwhelming database of interrelated observations and phenomenology that to doubt their very existence borders on the absurd. When the observational smoking guns of our era appeared, there was immense gratification – but no real surprise.



Prof Steven Balbus

Cover image: An artist's reconstruction of the tidal event ASASSN-14li, the object under study by Professor Steven Balbus and his student Andrew Mummery. A wandering star, too close to a supermassive black hole in a distant galaxy, has been pulled apart by the enormous tidal forces present. The stellar remnant has gathered into an evolving accretion disc, which the Oxford team has modelled using mathematical tools they have developed. Their work shows not only that a disc is certainly present, it also has provided important new information on the basic structure of relativistic discs.



Artist's impression of the tidal disruption event named ASASSN-14li, where a star wandering too close to a 3-million-solar-mass black hole was torn apart. The debris gathered into an accretion disk around the black hole.

EVIDENCE SUGGESTS THAT EVERY GALAXY IN THE UNIVERSE IS LIKELY TO CONTAIN A SUPERMASSIVE BLACK HOLE, WITH MILLIONS OF SOLAR MASSES OR MORE IN THEIR CENTRE

SUPERMASSIVE BLACK HOLES AND TIDAL DISRUPTION EVENTS

The evidence now suggests that every galaxy in the Universe is likely to harbour a supermassive black hole, with millions of solar masses if not more in their centre. These data have been very hard-won. Developing search strategies, in 1988 Martin Rees resurrected an earlier failed scenario in which the tidal disruption of stars could provide the fuel needed for the central black holes of quasars. He suggested that the same process might still produce observable, one-off events. These would take the form of a flaring X-ray outburst in an ordinary galaxy – perhaps even our very own. The idea behind these tidal disruption events (TDEs) is that a star which happens to venture too close on its orbit to a supermassive black hole would be tidally torn apart, in its entirety, by the differential gravitational force. The stellar debris would then rain back down onto the black hole, with a characteristic radiation emission profile that decays as a power law with time. Rees argued that if the debris were distributed with equal mass in equal energy intervals, simple Keplerian dynamics yields a luminosity that falls off with time t as $t^{-5/3}$. Since only a massive central black hole could provide the requisite tidal force to suddenly rip apart an entire star, the -5/3 light curve power law became a hallmark signature for X-ray black hole hunters searching for transient sources.

If one knows what one is looking for, it is all too easy to find. Thus, when the initial searches for TDEs not only found candidates, but apparent fits to -5/3 power laws, the theory seemed vindicated. Matters turned out to be a bit more complicated, however. One never sees an outburst at inception, so the initial time t_0 is unknown, and different choices of t_0 in the real world of messy data give different indices. There was also the question of whether a particular X-ray flare is truly a TDE or one of the many other, more standard types of known burst sources. Finally, how well could a candidate source location be identified with a galactic centre? If it is a TDE, it should be a spot-on bullseye.

The theorists, meanwhile, had their own concerns. What if the late stages of TDE accretion is not by direct fall back onto the hole, but by the formation and mediation of a disc? This is certainly a possibility! What is the time dependence of the luminosity expected from a steadily draining accretion disc? This turns out to be a very interesting physics question involving fundamental concepts of rotating fluid orbits in general relativity.

ORBITS AND STRESS AROUND BLACK HOLES

In Newtonian gravity, the angular momentum of a circular orbit is proportional to the square root of the distance from the central mass. It therefore increases outwards. This is important: were it to decrease outwards, circular orbits would be unstable, a result first proved by Lord Rayleigh. In general relativity, this angular momentum inversion of circular orbits actually occurs in the innermost disc regions, not too far from the hole's event horizon. Where circular orbits are unstable, the orbits plunge inward and there is very little disc to speak of. Therefore, a black hole disc sharply cuts off at the radius just inwards of the innermost stable circular orbit (ISCO).

The 'stress' is a tensor measuring the flow of momentum in a fluid: x-momentum, for example, that is transported in the y-direction. For accretion to proceed, we must transport the angular momentum from the rotating flow (designated as φ) towards the outward radial (r) direction. The $r\ \varphi$ component of the stress tensor is a very important quantity! Besides transporting angular momentum, the stress also serves to extract energy from the large scale differential rotation of the disc gas. Local turbulence immediately dissipates that free energy, heating everything up. In general, stress may be present from viscosity, turbulence, or even magnetic fields. In treacle, the stress is overwhelmingly viscous, but in astronomical accretion discs it is turbulent magnetic fields that dominate.

In the early days of accretion disc theory, the origin of this important stress tensor was poorly understood. For lack of any better idea, it was modelled as an enhanced viscosity. (The understanding that embedded magnetic fields naturally lead to a turbulent stress came in the 1990s, through work that I did with John Hawley.) A viscous stress would vanish at the edge of a disc (ie the ISCO), so this boundary condition was, in effect, universally adopted. The problem is that magnetic stress works differently to a viscosity. There is no reason that it should vanish at the ISCO, even as the gas starts its in-spiralling plummet.

UNDERSTANDING DISC SPECTRA

A key aim of black hole astrophysics is to be able to observe the emergent

Right: LIGO Laboratory operates two detector sites, one near Hanford in eastern Washington, and another near Livingston, Louisiana. This photo shows the Livingston detector site.

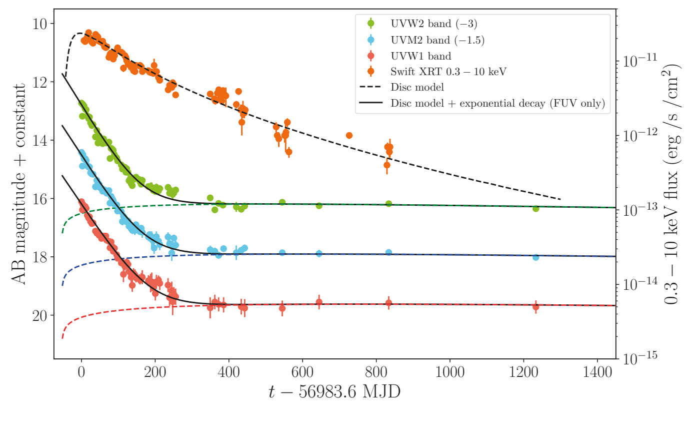


Fig. 1

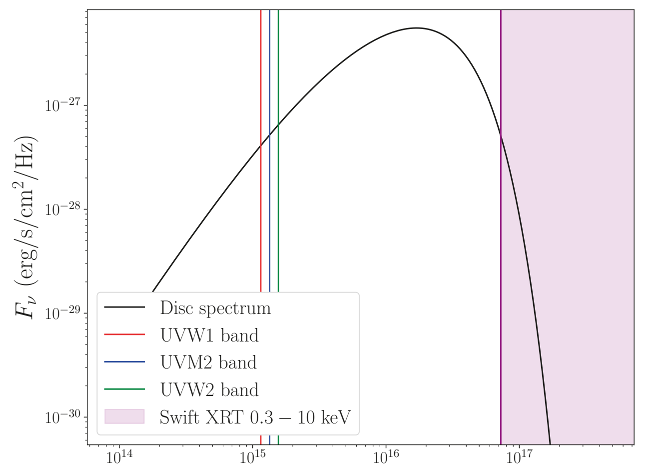


Fig. 2

spectrum and deduce the hole's mass and angular momentum. We have noted that the physics of the accretion process must be very well-understood if this scheme is to work, and such a crude uncertainty as not knowing the proper ISCO boundary condition renders this hope all but futile. So theorists found themselves constantly arguing about the ISCO stress.

Is it possible to deduce the ISCO stress from the disc spectrum? While in principle the answer is yes, for steady accretion this turns out to be very challenging to do, because its spectral influence is small. However, in an evolving disc, such as one might expect to find in a TDE, the answer that my student Andrew Mummery and I have found is much more interesting. We derived and solved the general relativistic equation for the evolution of a disc in Kerr geometry. As in the original Rees 1988 model, the total luminosity follows a power law time dependence at late times, $L\sim t^{-n}$. But now, the value of n turns out to have a bimodal behaviour. If the ISCO stress vanishes, $n>1$. If the ISCO stress is finite, $n<1$. Very convenient!

In 2017, a comprehensive study by K Auchettl, J Guillochon, and E Ramirez-Ruiz distilled, from a long list of candidates, four 'confirmed' TDE events based on a list of strict criteria, including a bullseye association with a galactic centre. Every one of their four candidates has power law X-ray luminosities with an index $n<1$. This is very strong evidence, not only for a disc to source the TDE emission, but one with a finite ISCO stress.

Emboldened by this success, Andrew has calculated detailed disc spectra based on both the narrow (far ultra-violet, or FUV) and broad (X-ray) band passes of the *Swift* X-ray satellite for the source known as ASSASN-14li. The acronym comes from the All Sky Survey of Automated Supernovae, a programme that is also well-suited to finding transient TDEs. ASSASN-14li has been observed over an extended period after its initial 2014 flare-up, and there are high-quality X-ray and FUV data. These are shown in fig. 1, along with fits to a single disc model.

The narrow FUV bands are observed to be very flat with time. This is completely consistent with a disc model. A disc spectrum is a superposition of local blackbodies. A readily identifiable Rayleigh-Jeans tail, peak, and Wien-like exponential cut-off are all present (see fig. 2). As a disc evolves and cools, the emission peak moves downwards in frequency. At a given observed frequency, just before the peak, the emission would therefore rise as the hump passed through, like a wave. But counteracting this rise at all frequencies is a general decline from cooling. For an extended time period, the rise and decline turn out to nearly balance one another. This is precisely what the FUV data show, in all three bands.

The X-rays tell a different story. Here, the emission comes from the Wien-like portion of the spectrum, and as time evolves, there is exponential decline with a power law coefficient. This combination fits the data beautifully as well. Both the FUV and the X-rays are reproduced by a single disc model. One of the by-products of the analysis of particular observational interest is an explicit, yet very general, mathematical prediction of the form that the decline in high energy X-ray luminosity should follow: neither a power law, nor pure exponential, but a simple product of the two, which mimics a power law over a restricted sampling interval.

CONCLUSION

LIGO and its sister observatories have made black hole gravitational radiation studies an indispensable component of the toolbox of modern astronomy. The astrophysical origin of the merging black hole binaries that form the bulk of gravitational wave sources is a stimulating puzzle for astronomers. The formalism for theoretical accretion disc studies, developed to help the early search for black holes, has meanwhile taken on a life of its own. Andrew Mummery and I have pushed the development of disc theory a step further, developing mathematical tools to study novel astrophysical events: the tidal destruction of a star passing close to a supermassive black hole. We are able to account for the disc emission spectrum of the one well-observed source, ASSASN14-li, in the process showing that this truly is a disc source with a *finite* ISCO stress (the strongest observational argument for this thus far advanced), and tightly constraining the mass of the black hole (just shy of two million solar masses). With most of the richest observations yet to come, the study of the tidal disruption of stars by supermassive black holes promises to remain lively and exciting for the foreseeable future.

Fig. 1: The top curve shows a theoretical fit to the light curve of the integrated X-ray spectrum of the Swift satellite, from 0.3 keV to 10 keV. It is well fit by the product of a declining power law and exponential cut-off in time. The three curves below are narrow FUV bands, fit without changing the X-ray inferred disc parameters. The FUV emission is quite flat with time.

Fig. 2: A typical disc spectrum at one point in time. It is broader than a single temperature blackbody, but has an identifiable low frequency (Rayleigh-Jeans), mid frequency (power law), and high frequency (Wien) regimes. The narrow FUV bands are shown as coloured lines; the broad Swift X-ray bandpass is shaded.

DISCOVERY OF MAGNETIC MONOPOLE NOISE

The nineteenth century saw teams of explorers from around the world take to the ices in search of the poles. The twenty-first century has again seen teams pulling together to find the poles – but this time, the task is to isolate the individual poles of a magnet. It is not the icy expanses of the tundra which we search, but insulating crystals known as 'spin ice'...

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Dr Felix Flicker

Prof Stephen J Blundell

Prof Séamus Davis

THE ELUSIVE MAGNETIC MONOPOLE

Our unified understanding of electricity and magnetism is encapsulated in Maxwell's equations. These describe the effects of point-like electric charges (electric monopoles) on the statics and dynamics of the electric and magnetic fields. One of Maxwell's equations can be stated in words: 'there is no such thing as magnetic charge' because no sources or sinks of magnetic field (magnetic monopoles) are described in the theory. But Maxwell's equation merely quantifies the experimental observation that we've never seen a magnetic monopole. If we detected magnetic monopoles, the law would have to be updated.

There are reasons to think such an observation may be possible. Some implications of the existence of magnetic monopoles in a quantum theory were discussed by Paul Dirac as early as 1931. Dirac noted that the existence of even a single magnetic monopole in our observable Universe would explain why all electric charge is quantised. Dirac's description also made clear that, in order to avoid the quantum phase of the electron becoming observable, there must exist an unobservable ('gauge-dependent') line of magnetic flux tethering any monopole to an anti-monopole. We now term this a 'Dirac String'. Moreover, magnetic monopoles are predicted by modern theories of physics 'beyond the standard model', including string theories and various theories of quantum gravity.

Particle physics searches for fundamental magnetic monopoles have been ongoing since the 1970s. Such a magnetic charge can, in principle, be detected by the quantised jump in magnetic flux Φ it generates upon passing through the loop of a superconducting quantum interference device (SQUID). Fig. 1 shows a schematic of such a SQUID-based magnetic monopole detector.

Using this classic technique, a single apparent observation of a fundamental magnetic monopole on 14 February 1982 (the St Valentine's Day Monopole) was never duplicated, and subsequent searches have proven negative.

A SOLUTION EMERGES

All is not lost, however, because condensed matter physics can come to the rescue. Condensed matter physics, while not concerned with fundamental particles, allows the appearance of quasiparticles with emergent properties. We live in a Universe which is filled with quantum fields and we regard particles as excitations of those fields. However, inside a solid there is a periodic arrangement of atoms with mobile electrons that can be so strongly interacting as to generate their own very exotic quantum fields. The net result of these interactions is that new particles can then emerge as excitations of the quantum fields in the low-energy sector of the Hamiltonian of the solid. This means that each type of condensed quantum matter that we study is a new Universe, with a different set of rules, and a different set of emergent particles. Can we therefore find a material in which the emergent particles are monopoles?

Let's build things up slowly. If we start thinking about building a periodic material in one-dimension, we can imagine a one-dimensional chain of magnets, each one lying with its north pole next to its neighbour's south pole. This is a stable situation and we simply have a line of dipoles. But we can imagine reversing one of these magnets. This creates two adjacent north poles and two adjacent south poles, not an energetically favourable situation. By flipping further magnets, we can move

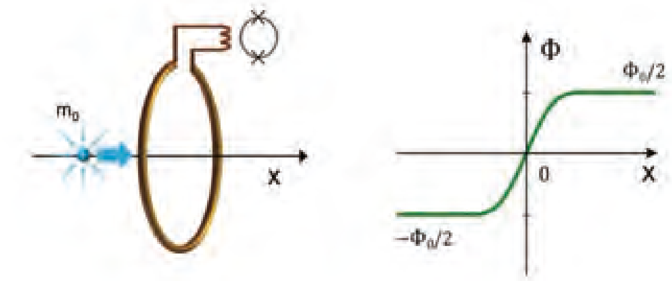


Fig. 1

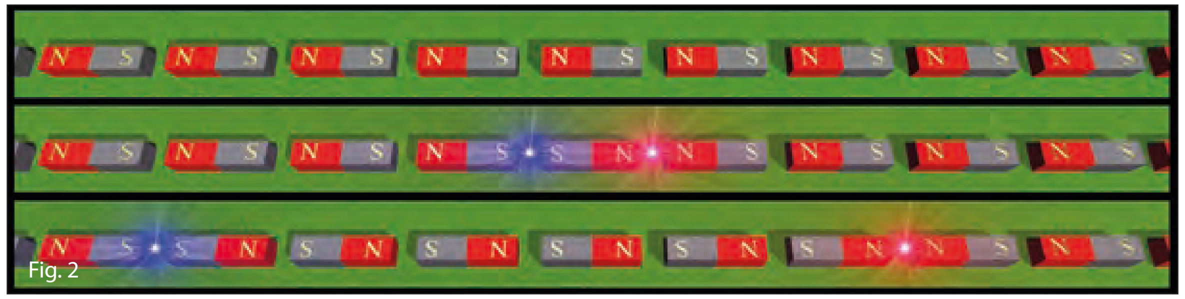


Fig. 2

Right: Fig. 1: Schematic of a fundamental Dirac monopole traversing the SQUID input coil. The magnetic-flux threading of the SQUID changes in total by $\Phi_0 = h/e$.

Bottom: Fig. 2: A line of bar magnets (top panel) ordered with north poles on the left and south poles on the right. Flipping one of them (middle panel) costs energy because you have two adjacent poles of the same type. Further magnet flips (bottom panel) cost little energy but separate the monopoles.

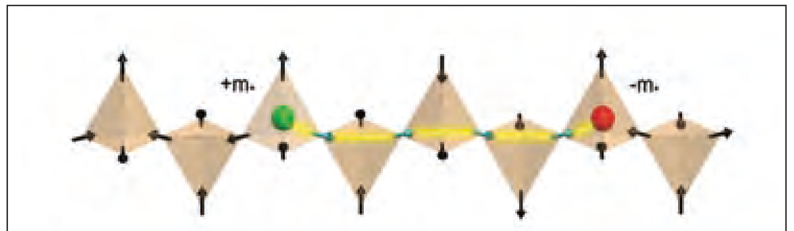


Fig. 3

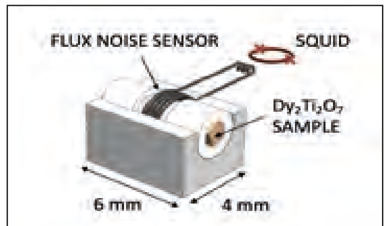


Fig. 4

Fig. 3: Schematic representation of the spin ice excited state in which two magnetic charges are generated by a spin flip and propagated through the material.

Fig. 4: Schematic of the Spin Noise Spectrometer.

the double-north and the double-south apart without much extra energetic cost. You can see that where we started with one flipped dipole, we now have two objects that behave like independent particles that can travel along the chain. Breaking a magnetic dipole in two, we have made two independent magnetic monopoles. In the jargon, our original excitation (the flipped magnet) has been fractionalised. The line of flipped spins between these emergent monopoles plays the role of the Dirac string.

THE ROUTE: SPIN ICE

The challenge in finding emergent magnetic monopoles, then, is to find a real material which performs this feat in three dimensions. Enter the spin ices (Fig. 3). The highly magnetic Dysprosium or Holmium ions in these materials live on a lattice of corner-sharing tetrahedra. The lowest-energy state of the system has the magnetic moments of two ions – their spins – pointing in, and two out, of each tetrahedron. This unusual property, discovered in crystals of dysprosium and holmium titanate by Steve Bramwell (UCL, DPhil Oxford) and Mark Harris (RAL, and later a Chaplain at Oriel College), led to these materials being called spin ices, by analogy with the proton configurations in water ice. The prediction of magnetic monopoles in this material, specifically because the two-in two-out configuration allows a chain of spin flips to occur during which an emergent magnetic monopole with magnetic charge +m* and anti-monopole with charge –m* can separate (Fig. 3), was made about ten years ago by Claudio Castelnovo and Roderich Moessner (both then at Oxford) along with Shivaji Sondhi of Princeton. Most of the world's supply of spin ices is grown in Oxford by Dharmalingham Prabhakaran.

THE EXPEDITION

The Oxford expedition in search of the poles began with a theoretical proposal to harness recent developments in nanoscale magnetometry[1]. The key realisation was that, while emergent magnetic monopoles would be confined within the spin ices, their magnetic fields could still be felt outside the sample. These fields feature a distinctive inverse-square law decay, as opposed to the inverse-cube law decay of the field from a magnetic dipole. The original proposal was that a sufficiently sensitive nanoscale detector of magnetic fields could, in principle, detect these magnetic fields at the surface of a spin ice sample. But very large numbers of emergent magnetic monopoles are expected to be moving around at random within the crystal, so that the magnetic fields should be wildly fluctuating. In this context, DPhil student Fran Kirschner, in collaboration with Felix Flicker in work led by Stephen Blundell, carried out numerical simulations of the magnitude and frequency dependence of the magnetic field noise that should be generated by a fluctuating fluid of magnetic monopoles.

Looking for a signature in fluctuations is an interesting approach, since physicists usually regard noise as the thing which has to be separated from the signal. But here the noise *is* the signal! In fact, it has been known for many years that the character of noise yields numerous clues explaining its origin. Noise has colour: white noise has a uniform power spectrum *S*, with equal intensity across all frequencies *f*: $S(f)\approx$const. Pink noise, on the other hand, has a power spectrum which falls off in inverse proportion to the frequency: $S(f) \propto 1/f$ (hence its other moniker, $1/f$ noise). Simulations showed that while the movement of the monopoles is random, it is also constrained by the presence of the Dirac strings. It turns out these constraints should also be revealed in the noise, which is predicted to fall off as $S(f) \propto 1/f^b$ with *b* between one and two (somewhere between pink and red), and varying characteristically with temperature.

Then in 2018, Séamus Davis and his group, intrigued by the ingenious proposal to find the poles using their magnetic noise, joined the expedition. In work conducted by DPhil student Ritika Dusad, they proposed to detect the predicted magnetic monopole noise by using the classic magnetic monopole detector – the input loop of a SQUID. Ritika developed a flux-noise spectrometer using a six-turn superconducting pickup coil (Fig. 4) connected to a SQUID, and optimised it for the predicted magnetic noise signal of $Dy_2Ti_2O_7$ spin ice. This is the condensed matter physics version of the classic magnetic monopole search apparatus shown in Fig. 1.

This set-up allowed the study of the magnetic-flux noise not just at the surface, but throughout the bulk of the crystal. They used it to determine the flux noise spectral density of the $Dy_2Ti_2O_7$ spin ice samples over a frequency range 1Hz$<f<$2.5kHz in the temperature range 1.2K$\leq T \leq$7K, both predicted to be optimal for detection of most intense magnetic noise spectra from the millimetre-scale $Dy_2Ti_2O_7$ crystal. The experiments were successful, revealing that mm-scale $Dy_2Ti_2O_7$ crystals spontaneously generate magnetic-field noise of magnitude 10^{-12} Tesla and below. They found that the magnetic-flux noise spectral density of $Dy_2Ti_2O_7$ is constant for frequencies from near 1Hz up to an angular frequency $\omega(T)\sim 1/\tau(T)$, above which it falls off as ω^{-b} where *b* spans a range between 1.2 and 1.5. They also observed the strange fact that had been predicted by the simulations, that the magnetic noise should increase rapidly with falling temperature proportional to $\tau(T)$. Thus, the SQUID-based flux-noise spectrometry experiments had detected (Fig. 5A) virtually all the features of the magnetic noise predicted for a dense fluid of magnetic monopoles (Fig. 5B). The team had found the poles[2].

There was also a striking bonus effect. As scientists, we are used to studying data plotted on graphs and we spend a lot of time looking at our data in lots of different ways to try to understand what is going on. Visualisation techniques are therefore key in physics. However, much less common is the opportunity to listen to our data. Extraordinarily, because this magnetic monopole noise occurs in the frequency range below 20 kHz, when amplified by the SQUID it is actually audible to humans.

AS SCIENTISTS, WE ARE USED TO STUDYING DATA PLOTTED ON GRAPHS AND WE SPEND A LOT OF TIME LOOKING AT OUR DATA IN LOTS OF DIFFERENT WAYS TO TRY TO UNDERSTAND WHAT IS GOING ON. MUCH LESS COMMON IS THE OPPORTUNITY TO LISTEN TO OUR DATA. LUCKILY THIS MAGNETIC MONOPOLE NOISE OCCURS IN THE FREQUENCY RANGE THAT IS AUDIBLE TO HUMANS.

Fig. 5. Left: simulated noise spectral density S(w, T) in temperature range 4K to ~1K which one might expect to achieve by cooling $Dy_2Ti_2O_7$.

Right: measured noise spectral density from $Dy_2Ti_2O_7$ samples in the range 1.2K≤T≤4K. Red axes indicate spectra scaled for B-fields, blue axes (matching scales) spectra scaled for magnetic flux.

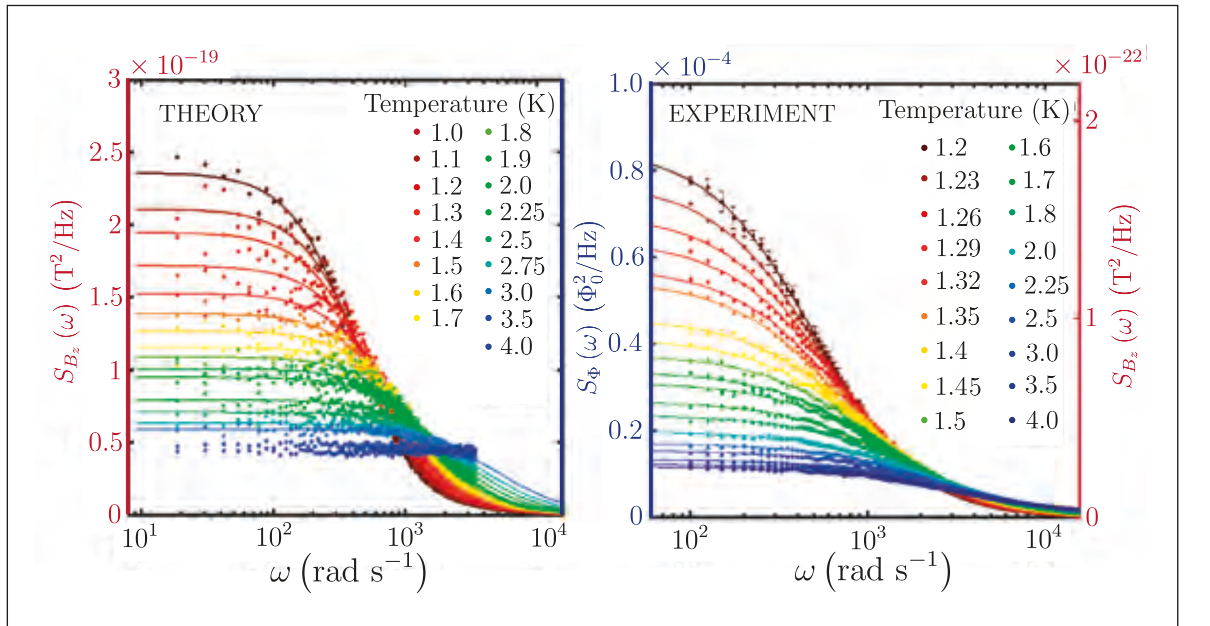


Fig. 5

NEW FRONTIERS

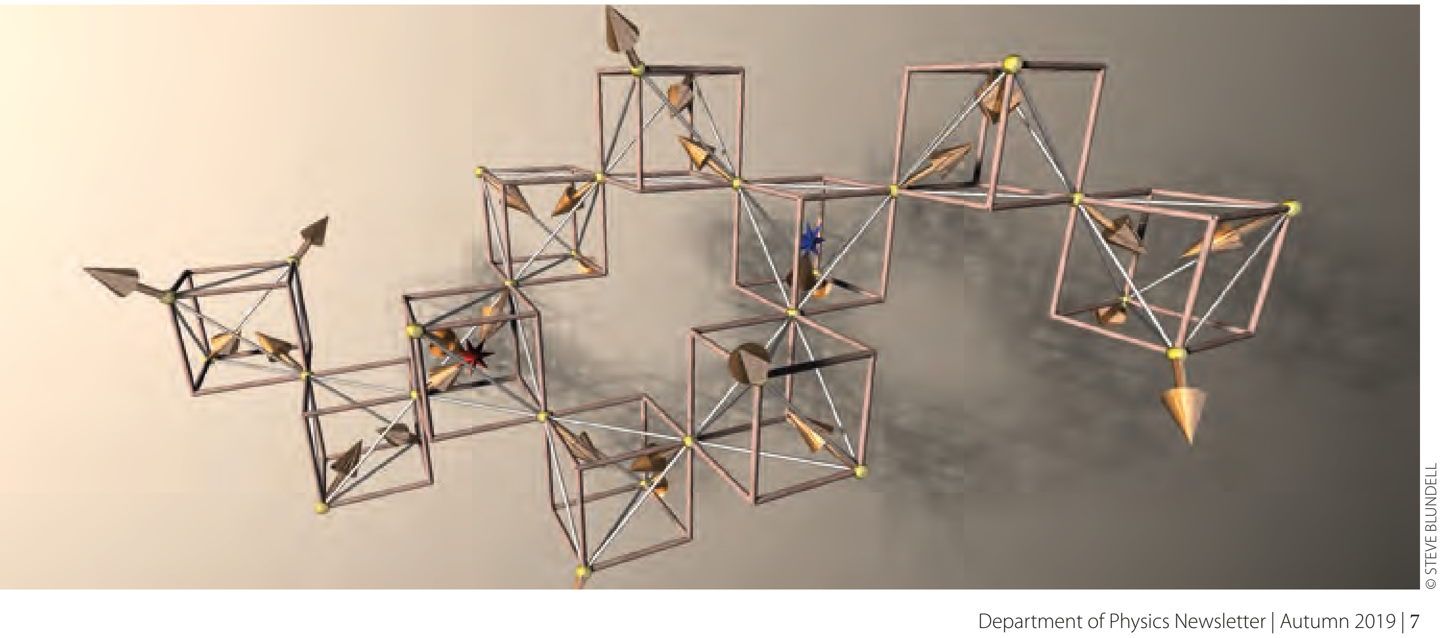
Returned from such an expedition, the explorer's thought must surely be to the next challenge. Possible applications for magnetic monopoles in spin ices include the creation and manipulation of 'magnetricity', a magnetic version of electricity. But the detection of a single magnetic monopole is still a key goal for this team. Our SQUID-based detection technique had provided the first experimental evidence of magnetic monopoles which has a single-particle limit: while we heard the collective noise of many monopoles, the same basic approach at yet higher sensitivity could in principle be used to detect individual magnetic monopoles. So, our follow-up projects have begun, to better understand the monopoles' noise signatures in different contexts; to detect the individual emergent magnetic monopoles; and to apply the same measurement techniques to explore other exotic magnetic systems.

Are Maxwell's equations still correct? No physics needs to be unlearned yet, as the monopoles in spin ice are emergent (for those that can remember their electromagnetism, these monopoles are divergences in H and not in B) and Maxwell's equations remain unbroken. But these results demonstrate the power of using spin noise spectroscopy to study many different exotic magnetic systems which will contain numerous different species of emergent particles. Rather than wait for the Universe to deliver a rare, exotic magnetic particle to a detector, one can now explore the universes of quantum matter, studying such particles by the noise and eventually the signal they produce.

1 F K K Kirschner, F Flicker, A Yacoby, N Y Yao, and S J Blundell, Proposal for the detection of magnetic monopoles in spin ice via nanoscale magnetometry, *Physical Review* B 97, 140402 (Rapid Communications) (2018)

2 R Dusad, F K K Kirschner, J C Hoke, B R Roberts, A Eyal, F Flicker, G M Luke, S J Blundell and J C S Davis, Magnetic Monopole Noise, *Nature* 571, 234-239 (2019)

Below: An artist's impression of spin ice monopoles.



MEASURING ATMOSPHERIC TEMPERATURE FROM SPACE

A theoretical concept put to the test by Oxford's first space instrument now plays a key role in weather forecasting

Prof Anu Dudhia

Next year will be the 50th anniversary of Oxford's first venture into space. The Nimbus-4 satellite, launched on 8 April 1970, carried a suite of meteorological instruments, including the Selective Chopper Radiometer (SCR), developed in the Atmospheric Physics Department – one of the first instruments to provide global measurements of atmospheric temperature.

Led by John Houghton[1], the department had already flown high-altitude balloon and aircraft experiments to measure the infrared radiation emitted by the atmosphere within the 15 μm CO_2 band. These measurements could then be used to infer the atmospheric temperature structure. The Nimbus-4 SCR demonstrated that satellites could provide such data on a global scale, and within a couple of years similar instruments had become core components of the operational polar-orbiting meteorological satellites.

The SCR was the size of a large shoebox and weighed just over 2 kg, while the current generation of instruments are about a factor 100 larger in both mass and volume (and probably rather more in cost). However, they still exploit the same underlying physics.

THE INFRARED ABSORPTION SPECTRUM

The main processes that determine the infrared radiation emerging from the top of the atmosphere are shown in Fig. 1 (this is for a cloud-free situation; clouds are as opaque in the infrared as they are in the visible).

For wavelengths longer than 4 μm, reflected sunlight becomes negligible and the main radiation source at the base of the atmosphere comes from the Earth's surface itself, emitting (to a fair approximation) as a black body.

A number of molecules have vibration-rotation bands which are excited at these wavelengths so, apart from a few 'window' regions, most photons are absorbed in the atmosphere. Notably absent from the list of absorbers are the two most abundant atmospheric molecules, nitrogen and oxygen. Being symmetric molecules, these have no permanent dipole moment, so interact only weakly with electromagnetic radiation.

As the excited molecules relax, they re-emit the photons. However, since the atmosphere is generally colder than the surface, the re-emission is at a lower intensity, so the net energy reaching space is reduced, resulting in absorption bands (similar to the Fraunhofer lines in the solar spectrum). The 'missing' energy is re-radiated downwards, warming the surface instead – the well-known 'greenhouse effect'.

TEMPERATURE SOUNDING

Given a radiance measurement at particular wavelength, we can invert the Planck function to find the atmospheric temperature at the photon's source. For absorption features of a molecule of known concentration, such as CO_2, we can calculate the emitting altitude as a function of wavelength: the stronger the absorption, the higher the altitude. So then it is just a case of selecting spectral points whose emissions span the depth of the atmosphere (see Fig. 2).

Having established the temperature structure, we can then use the radiance measurements in other regions of the spectrum to determine the concentrations of the variable absorbers, water vapour being the most important for weather forecasting.

CURRENT INSTRUMENTS

The original infrared sounders were radiometers, using 10 or so spectral filters to isolate specific channels sensitive to different altitudes (although this simple statement barely does justice to the ingenuity that went into some of these designs, particularly in improving sensitivity to the high altitudes).

About ten years ago these were replaced by Michelson-type interferometers. These provide complete infrared spectra, effectively thousands of channels, from which to extract information on temperature and composition. The spectrum plotted in Fig. 2 was actually obtained from one such instrument: the Infrared Atmospheric Sounding Interferometer (IASI).

The data rate from such instruments is daunting: each IASI instrument (and there are currently three in operation) provides over a million spectra a day. The routine processing of such a large data stream to derive profiles of temperature, water vapour and other major absorbers is now performed by specialist agencies, so what does that leave for University research groups?

These spectra also contain signatures of many minor species, associated with pollution events or volcanic eruptions. In AOPP we are devising numerically efficient algorithms to identify, and preferably quantify, such occurrences.

Meanwhile, exploiting recent advances in 'microsat' technology, we are also planning new space experiments where not just the instrument, but the entire satellite would fit into a large shoebox (Fig. 4).

1 Subsequently Director General of the Met Office and co-chairman of the Intergovernmental Panel on Climate Change

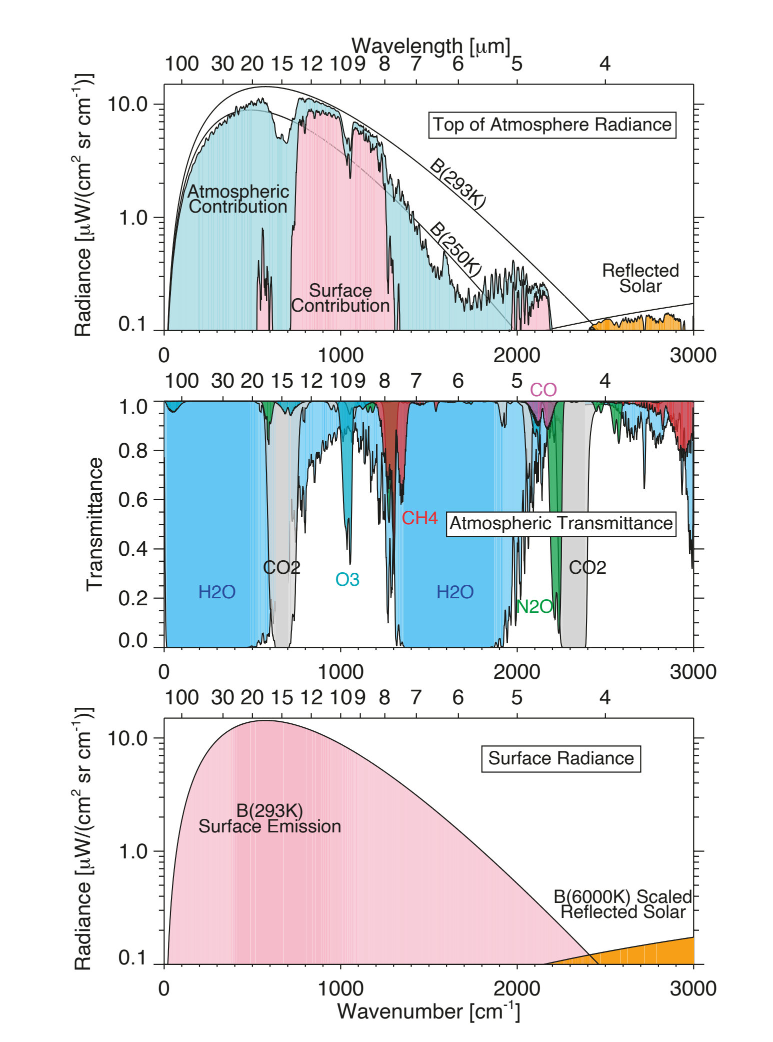


Fig. 1

Left: Fig. 1: The main processes governing infrared radiative transfer in a cloud-free atmosphere. The solar contribution has been scaled to represent the same total energy as the surface emission. B(T) represents Planck function, evaluated for temperature T. Note the definition of 'Wavenumber', as commonly used in infrared spectroscopy, is the simple reciprocal of the wavelength and conventionally measured in inverse centimetres.

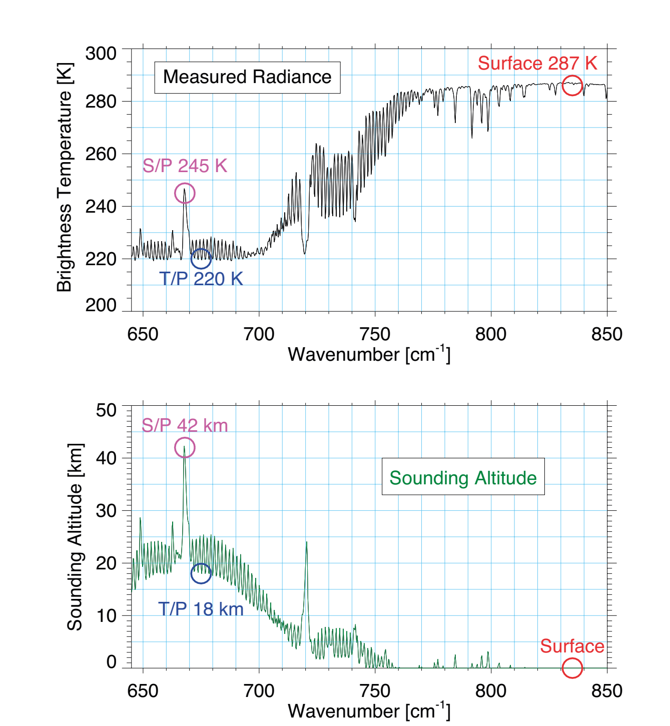


Fig. 2

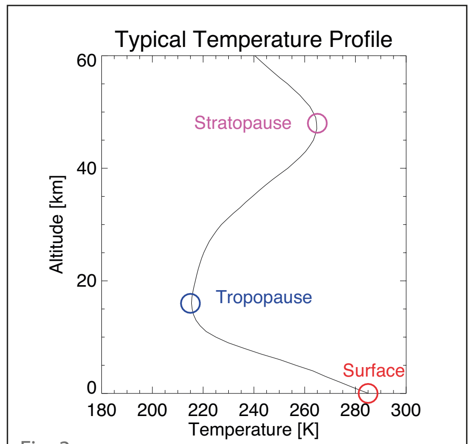


Fig. 3

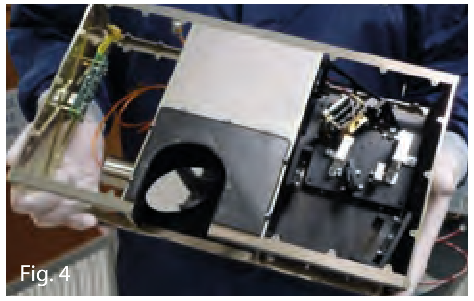


Fig. 4

Right: Fig. 2: The top panel shows part of the top-of-atmosphere radiance spectrum from approximately 15–12 μm extending from the CO_2 absorption band into the adjacent atmospheric window region. The measured radiance is expressed as an equivalent temperature, using the inverse of the Planck function. The lower panel shows the corresponding sounding altitude, defined as the altitude where transmittance from the top of the atmosphere drops to 1/e. See Fig. 3 for location of max/min points on the atmospheric temperature profile.

Far right: Fig. 3: Typical atmospheric temperature profile, showing the temperature maxima/minima identified in the spectrum shown in Fig. 2.

Bottom right: Fig. 4: A full-size prototype CubeSat spacecraft with an infrared radiometer, being developed by DPhil student Rory Evans.

An artist's drawing of the general design of the Nimbus series of satellites. The solar-panel 'wings' move throughout the day to track the Sun during the daylight part of the satellite's orbit. The 10-foot-tall satellite has the attitude control system on top, separated from a 5-foot-diameter 'sensory ring' (centre) with scaffolding. The sensory ring holds the batteries and electronics for each of the sensors that are mounted underneath the ring (bottom).

IMAGE TAKEN FROM MADRID, C R, ED. (1978) *THE NIMBUS 7 USERS' GUIDE*. GODDARD SPACE FLIGHT CENTER: NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

OXFORD LEADS QUANTUM RACE

www.physics.ox.ac.uk/enterprise

"What kind of computer are we going to use to simulate physics? Can you do it with a new kind of computer – a quantum computer?" — *Richard Feynman, 1982*

Advances in technology since the 1960s have enabled silicon transistors to keep shrinking, allowing exponential growth in computational capability. However, they are now so small that the laws of quantum mechanics begin to impair their performance and cannot shrink much further. The continuous breakthroughs in science that have been enabled by this computing growth are now becoming limited. However, with an understanding of quantum mechanical behaviour, new possibilities for computation are being explored. Can the computer postulated by Richard Feynman now be realised? A computer that relies fundamentally on quantum mechanics can potentially solve many important computational problems faced by businesses that will remain forever intractable using conventional computers.

THE GLOBAL RACE

'Quantum technologies' utilise the unique phenomena of quantum superposition and entanglement to encode and process information, with potentially profound benefits to a wide range of information technologies, from communications to sensing and computing. However, a major challenge in developing these technologies is that the quantum phenomena are very fragile, and only a handful of physical systems have been identified in which they survive long enough and are sufficiently controllable to be useful.

In 1999, the 'world's first quantum computing company' D-Wave Systems Inc. was spun-out from the University of British Columbia, founded by two physicists and a local venture-capitalist who provided the first $3000. Twenty years later (and despite some scepticism from the quantum computing community), the company has gone on to raise over $200m including investments from Jeff Bezos (founder of Amazon) and In-Q-Tel, the venture-capital arm of the CIA. Their first customers were Lockheed Martin, who were looking for a way to tackle particularly tough optimisation problems in their flight control systems, followed by Google and NASA. Although D-Wave were the first to market, there is a bigger story developing, with the UK and Oxford Physics amongst the leaders in creating a quantum technology industry.

To support and capitalise on the UK's world-leading academic quantum physics research groups, the UK Government announced in 2013, funding of £270m to create a five year National Quantum Technologies Programme, which aimed to accelerate commercialisation by creating a coherent community across Government, industry and academia. It involved over 130 companies, 17 universities and various government agencies. Four research hubs were created to support collaboration and to provide facilities and training, which focused on applications in timekeeping, sensing, imaging, communications and computing. Oxford Physics led the Networked Quantum Information Technologies Hub (NQIT), bringing together 200 researchers from across the University with the aim to prototype the basic components of a quantum computer, which may eventually be scaled-up to produce a universal quantum computer. But the UK was not alone in this investment, with the international race for quantum technology underway and attracting enormous research funding, including $1b over 10 years in Europe, $4b over five years in China, $1.2b over five years in the USA and hundreds of millions by several multinational companies including Microsoft, Google, IBM and Intel. The goal of NQIT was, in collaboration with government, industry and the wider community, to develop the first truly scalable universal quantum computing machine with architectures that have the highest performance of any current qubit system. Aligned to this was the aim to build a new industry sector around quantum information technology, from the supply chain, through the build and operation, to programming and use of quantum computers. The NQIT Consortium saw an alliance of nine universities led by Oxford, plus more than 30 commercial and government organisations including IBM, Lockheed Martin, Raytheon, Google, Toshiba, Oxford Instruments, the National Physics Laboratory and the Defence Science and Technology Laboratory.

We could map the whole Universe – all of the information that has existed since the Big Bang – onto 300 qubits.
Seth Lloyd, MIT

OXFORD INVENTIONS

Qubits in superposition are extremely sensitive to external stimuli, with the slightest disturbance causing them to collapse, introducing errors into the calculations being carried out.

© JACK HOBHOUSE

Dr Phillip Tait and NQIT

NQIT ACHIEVEMENTS

4 world records IN ION TRAP QUANTUM COMPUTING

61 RESEARCH PAPERS PRODUCED

ENGAGED WITH **140+ companies**, NATIONAL AND INTERNATIONAL

34 INDUSTRY-PARTNERED PROJECTS

5 SPIN-OUT COMPANIES

Left: Postdoctoral researchers Dr Brian Vlastakis and Dr Martina Esposito preparing an experiment on superconducting devices in a dilution refrigeration system.

The quantum computing and simulation hub will drive forward the UK's progress in developing future quantum computing technology. It will build on the successes of the Oxford-led 'Phase 1' NQIT hub, which has delivered world-leading performance in quantum logic and quantum networking, as well as a number of spin-out companies to take quantum research out of the lab and into the commercial arena.
— Prof David Lucas, Oxford Physics, principal investigator for the new hub.

© RUPESH SRIVASTAVA

DPhil student Amy Hughes working with optics for ion traps.

Top right: A single positively-charged strontium atom, held near motionless by electric fields emanating from the metal electrodes surrounding it. The distance between the needle tips is 2.3 mm. When illuminated by a laser, the atom absorbs and re-emits light particles sufficiently quickly to capture it in a long exposure photograph. The picture was taken by DPhil student David Nadlinger.

Commercial applications of quantum computing

- Use alongside machine learning and AI to make better predictions from medical data;
- Speed up engineering processes such as material modelling;
- Produce higher efficiencies and productivity or more reliable complex systems in sectors such as meteorology;
- Offer exponential growth in computation speed and power for systems, such as those used in global financial trading;
- Verification and validation of complex or critical systems, including aerospace and automotive industries.

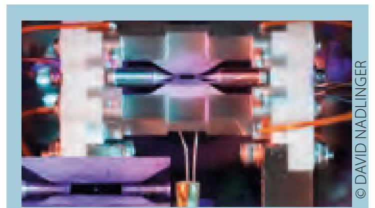
Adding extra qubits to a system and getting them to talk to one another, and thus build a computer that can crack the toughest calculations, is a significant challenge in physics and engineering. Oxford physicists are pioneering two different technological approaches for the 'processors' that could form a quantum computer, with each looking for the balance between ease/cost of manufacture and fidelity (its resistance to decoherence). One method has each processing node as an ion trap, a device within which a small number of charged atoms – ions – are held suspended in a vacuum and manipulated by laser and microwave systems. A single unit of quantum information, one qubit, is embodied within the internal hyperfine states of each ion, and control of the qubits is achieved optically via integrated lasers and through microwave manipulation.

This technology has attracted significant interest from investors and earlier this year a spin-out company, Oxford Ionics, was founded by physicists Dr Chris Ballance and Dr Thomas Harty from the ion-trap group, to take forward its commercialisation.

Another method being developed here uses superconducting circuits for the quantum computer's architecture. This approach exploits the quantum mechanical behaviour of electrical circuits when operated at microwave frequencies and at a temperature near absolute zero and has been used by companies such as D-Wave, IBM and Google for their quantum computing systems. To support further development of Oxford's intellectual property in this area, a spin-out company, Oxford Quantum Circuits, was founded in 2017 by Dr Peter Leek, to build scalable components for a quantum computer.

NEXT STEPS

The Government Office for Science predicts that quantum technologies could grow to be comparable in size to the consumer electronics sector (currently worth an estimated £240bn a year globally) and potentially create hundreds or thousands of high value jobs in the UK. To realise this potential, the UK government's National Quantum Technologies Programme has now entered its second phase of funding, a £315 million investment in a National Quantum Computing Centre and four research hubs, including a Quantum Computing and Simulation hub led by Oxford University. This hub will bring together research teams across 17 universities with more than 25 national and international commercial, governmental and academic entities. Alongside the hardware development, researchers are developing the software systems to program and operate a quantum computing machine and are working on our own quantum computing emulator platform for high-performance computers, which will enable scientists in research and industry to develop algorithms and applications for the emerging hardware.



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Qubit — Conventional computers store data in 'bits' that can exist in only one of two states (0 or 1); different combinations of 0s and 1s are used to represent letters and numbers. A quantum computer would store data in 'qubits', which due to quantum superposition, could be both 0 and 1 at once. A group of qubits could occupy all possible combinations of 0s and 1s simultaneously, enabling the computer to explore multiple solutions at the same time.

Superposition — an ambiguous state in which a particle (eg an electron) is simultaneously spinning both clockwise and anticlockwise, or '0' and '1'. However, once it is measured or interacts with its environment, it settles into a single state.

Entanglement — a physical phenomenon that occurs when pairs or groups of particles are generated or interact in ways such that the quantum state of each particle cannot be described independently. This means that a measurement made on one particle will determine the outcome of a similar measurement made on the other particle, even over great distances. Albert Einstein famously referred to this phenomenon as 'spooky action at a distance'.

Coherence — the ability of a qubit to maintain superposition over time. It is therefore the absence of 'decoherence', which is any process that collapses the quantum state into a classical state, for instance by interaction with an environment.

Engaging with the future users of quantum computers both in academia and industry has been a central part of NQIT's mission, from collaborations with the supply chain to supporting and engaging with the emerging software sector, and growing a base of skills and awareness. The new hub will continue this work of helping businesses prepare for all aspects of the emerging quantum information technology economy. Oxford University's leading role has opened the possibility of the region becoming a UK home for this revolutionary technology, with significant investment in our research and university spin-outs, as well as local start-ups that will build the components and capitalise on its capabilities. Are *you* quantum ready?

NOTES FROM THE HEAD OF PHYSICS

Prof Ian Shipsey, Head of Department

Each year as autumn begins, we eagerly anticipate the arrival of about 180 new undergraduate students and 90 graduate students to Oxford Physics. Naturally, we are reminded of our own first days at university, both the excitement and trepidation, and how the journey we each began that day shaped our lives. One of my first tasks as Head of Physics a year ago was to welcome the students and talk to them about Oxford Physics, the wonderful research that goes on here and the opportunities each of them will having during their time with us. Their excitement was as large as their potential is great. We must do all we can to realise it. When I address the students this year I will be able to share with them some good news on several fronts.

CUTTING EDGE RESEARCH

Thanks to the generosity of many of you, this year our students will be joined by the first OXPEG student and a student from the new Oxford partnership with the Max Planck Institutes. The research that our graduates perform is inspiring. Alex Savin is from a state school in East London and was admitted to Lady Margaret Hall in 2013. He finished in the top 10 of his cohort in 2016. He continued his doctoral work in Atomic Laser and Plasma Physics. His research on fundamental energy absorption processes in ultra-high intensity laser-matter interactions was published in *Nature's* Scientific Reports in June (**https://rdcu.be/bHkXR**). Alex was first author. Also on the same paper Ramy Aboushelbaya – an Egyptian student who was determined to be a physicist, despite limited opportunities in his own country. He went to France and was educated there for his BSc and MSc. He was admitted to Oxford Physics in 2016. In addition to the paper together with Alex, his remarkable work on fundamental light-matter interactions with pulses containing orbital angular momentum recently appeared in *Physical Review Letters* (**https://arxiv.org/abs/1902.05928**). Ramy is first author, and Alex is also on the paper.

A NEW BIOPHYSICS CHAIR

Thanks to the generosity of one of our alumni, we recently had the privilege to receive a gift of £6m – the largest single gift ever received by Oxford Physics – to create an endowed chair in biophysics. This has been a long term aspirational goal of the department. It will be our first chair in this rapidly evolving and increasingly important sub-discipline of physics. It has come at an excellent time: our biophysicists will soon move into new laboratories in the Dorothy Hodgkin Centre, currently under construction, while down the road at Harwell, UKRI is creating the Rosalind Franklin Institute 'dedicated to bringing about transformative changes in life science through interdisciplinary research and technology development', and where Oxford academics are set to play a leading role in shaping the science programmes.

ENTERPRISING PHYSICS

Our ongoing drive to develop a culture encouraging innovation and enterprise is bearing fruit. There is a significant increase in the formation of spin-out companies by our researchers, which now totals twelve. From our first spin-out in 1959 (Oxford Instruments) it took 50 years to reach a total of five but the next seven companies have come in the last four years, including three in the last 12 months. Our latest companies are working in the areas of quantum computing; weather prediction for the aviation industry; and artificial intelligence. With all twelve companies providing physics-based solutions to their customers and employing hundreds of people around the world, we are extremely proud of their success and are excited to see more of our researchers and students getting involved.

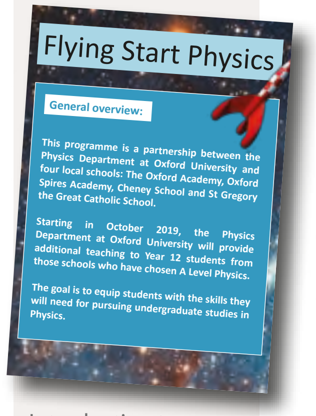
Aligned to this, in partnership with the Saïd Business School and the Oxford Foundry (the University's new entrepreneurship centre), we are developing a course on Physics Innovation and Entrepreneurship for those undergraduate and postgraduate students who wish to further their understanding and skills in creating businesses built on physics-based technology. The course, in a preliminary form, will go live this year. It will be taught by experts in their fields, will include modules on creative problem solving, intellectual property, understanding markets and creating business plans, and will use case studies that include our very own spin-outs.

FLYING START

We are developing exciting new programmes to increase access of under-represented groups to Oxford. This autumn will be the inaugural year for 'Flying Start'. This programme is a partnership between the Physics Department and four local Oxford schools: The Oxford Academy; Oxford Spires Academy; Cheney School; and St Gregory the Great Catholic School. We will provide additional teaching to Year 12 students from those schools who have chosen A-level Physics. The goal is to motivate students to study physics at university, and to equip them with the skills they will need to pursue undergraduate studies. The programme consists of weekly sessions of 1.5 hours during the eight weeks of each term. During each session the founder, Professor Caroline Terquem, will talk about one topic that builds on the knowledge of the students, with the aim to show how what they have learnt can be applied to understand the world around us. Problem solving sessions will alternate with lecture-style presentations. Then, at the end of each session, a researcher from the department will give a short talk about an exciting research project. Thanks to alumni support, bus transportation will be provided from, and back to, the schools, and the students will receive a snack when they arrive.

I look forward to giving you more news in the Spring edition of the newsletter. May you have a happy remainder of 2019, a peaceful holiday season, and a great start to 2020!

Ramy Aboushelbaya has been invited to address the American Physical Society's Division of Plasma Physics in Florida this October.



Introduction to Oxford's Flying Start programme, aimed to motivate year 12 students to study physics at university.

A lively physics undergroup group class.

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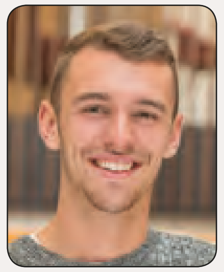
FIVE MINUTES WITH... ROWAN CURTIS

DPhil Atmospheric, Oceanic and Planetary Physics, Trinity College



@rowancurtis20

CONFIRMING THE PRESENCE OF WATER ICE ON THE MOON IS ONE OF THE BIG CURRENT CHALLENGES AND GOALS FOR LUNAR SCIENCE

Tell us a little bit about your background

I grew up in Southampton and then went on to study Physics at the University of Surrey, before undertaking various research placements to try to work out which direction I wanted to go in. I spent time researching quantum materials (Diamond Light Source Ltd), fiber optics (Optoelectronics Research Centre) and tissue engineering (University of Surrey) before deciding I wanted to move into space science. I'm now approaching the end of my first year studying for a DPhil within the AOPP sub-department.

When/how did you know you wanted to become a physicist?

It all started in a garden in Cornwall, when I was eight years old. My Dad explained to me what stars were and how we were looking at ancient starlight, which may have travelled for millions/billions of years before reaching our eyes. Later, I discovered the work of Einstein, and ever since, I've had this love and interest for physics that I can't shake. I have always been a bit of a philosopher at heart and I've found physics to be the most tangible way to study this absurd and beautiful Universe in which we find ourselves.

Why do you think it is important to study Physics?

Besides satisfying and provoking our natural curiosity – which is important in its own right – physics underpins the technologies which drive our modern world. Everything you do that requires a screen, an engine or a battery has been brought to life by the application of physics. As we look forward, it is Science that gives us hope of solving the ecological and climatological issues we so critically face. We need science as a whole to work together for future global prosperity and development, and physics will play a vital role in this.

Can you explain the work you do?

I study the temperature profiles of the polar regions of the lunar surface using NASA's Lunar Reconnaissance Orbiter (LRO) and laboratory data taken during my DPhil. This work aims to constrain the regions for which ice volatiles (such as water ice) may be trapped in cold, permanently shadowed regions of lunar polar craters. By studying these potential ice volatile deposits, we hope to learn more about the history of our Moon, our Solar System and even the origins of life.

What are the current challenges in your field?

Confirming the presence of water ice on the Moon is one of the big current challenges and goals for lunar science. Another challenge is to collect more samples from the lunar surface in order to improve our understanding of the Moon and the history of our solar system. Twelve people have walked on the Moon so far and, whilst doing so, set up experiments and collected samples from which we are still learning important things today. But it won't be easy to get people – men and women – back to the lunar surface safely, even with today's level of technology.

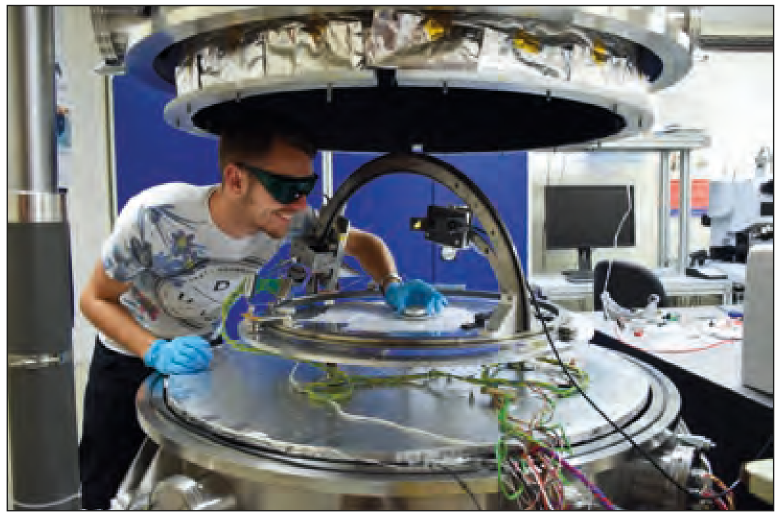


Image top right: Rowan participated with Prof Neil Bowles in this year's 'Thinking 3D' celebrations. He is pictured at the Weston Library during an outreach event.

Right: Rowan is studying heat transfer on airless bodies, such as asteroids and the Moon (with applications to NASA's LRO and OSIRIS-REx missions).

What other interests do you have besides physics?

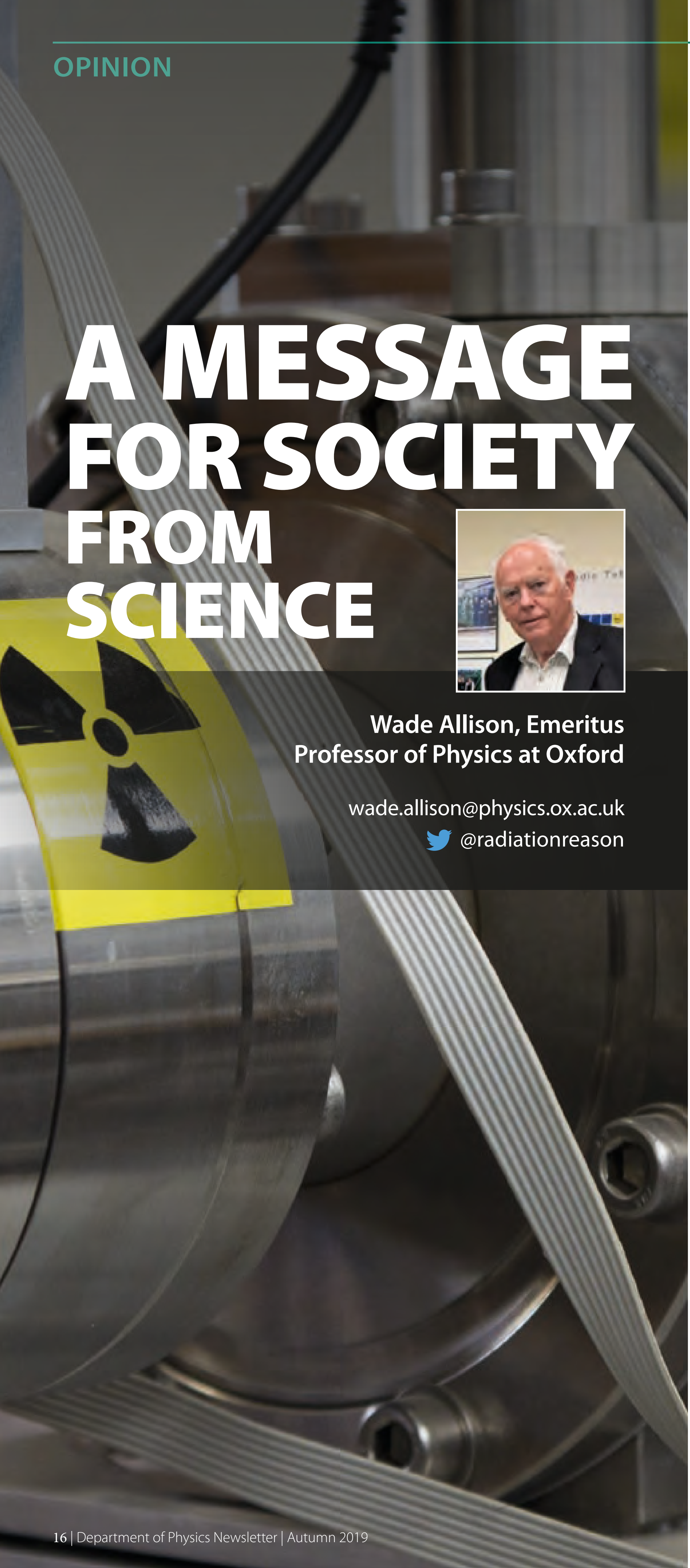
Music is a very important part of my life and I am a keen concert-goer, multi-instrumentalist and big band vocalist. I love literature, and write short stories, novels and poetry. I can be found frequenting the pubs of Oxford and am a lifelong supporter of Southampton FC.

Can you share the main positives of being a physics student at Oxford?

Being part of both the physics department and my sub-department (AOPP) (which throws amazing parties) has been a great experience, but for me the outstanding highlight of being a physics student at Oxford is the Collegiate system. Belonging to a college is fantastic, as you have so many beautiful minds around you. There is always someone to talk to at lunch or dinner, always someone who is in the mood for a discussion (whether it be about Nietzsche, Beethoven or Football) and always someone up for a game of pool. I cannot stress the importance of the collegiate system enough, in creating the social, pastoral and academic haven that has made my time at Oxford so special.

What advice would you give people who want to study physics?

Make sure you love physics. Life is too short to study things you don't love. If you do, immerse yourself in it. Be rigorous with the mathematics behind the concepts, but never lose sight of the concepts themselves. If you find you want to work in physics, try work placements in various fields to find which field you want to go into (and which ones you don't). Dig deep and you will find beauty; then the rewards will come.



A MESSAGE FOR SOCIETY FROM SCIENCE

Wade Allison, Emeritus Professor of Physics at Oxford

wade.allison@physics.ox.ac.uk

@radiationreason

'Is there life out there in the Universe?' is an exciting question, but perhaps a more urgent one is 'Will there be life here on Earth in 100 years?'

With the realisation that the climate is changing fast, this has become a matter for widespread concern. The combustion of carbon fuels was a foundation stone of the Industrial Revolution; replacing it successfully will bring a new revolution. To avoid social and economic instability, the right steps should be taken soon.

This is a question first for physics, and then for other academic disciplines too. Quite beyond the remit of any single research body this struck me as a task to tackle in my so-called retirement. Having researched at CERN and taught physics and maths in the Physics Department since the early '70s, including a lecture course on Medical and Environmental Physics, I had many of the tools. Since 2006, I have worked on the question with like-minded academics and professionals around the world. The hardest part is to present the task and its solution in a way that wider society is able to accept.

The basic characteristics of energy are that it is conserved and that, if left alone, it tends to dissipate – simple descriptions of the First and Second Laws of Thermodynamics. To replace carbon as a fuel, any new candidate fuel should be stable and make energy available whenever required. Furthermore, this fuel should be energised by some greater source, or have been so at some point in the past.

EXTERNAL POWER

Humans graduated from a reliance on the energy of the food they ate when they began to utilise the effort of fellow creatures and the various energy forms powered, directly or indirectly, by the Sun, including wind, water power and burning wood. With these they worked metal, built great cities and sailed the world. Though superior to other animals, their population was small, life expectancy short and standard of living miserable. For example, not until the Industrial Revolution did the population as a whole enjoy sports or annual holidays – at best they survived.

The energy density[1] of hydro power is low. Let's put in the numbers: for example, for water from a 100m-high dam, the density is 981 joules per kg. So, a modern gigawatt power station requires a million kg of water per second, ignoring inefficiencies. As a result, a hydro power plant has a huge footprint with a correspondingly destructive effect on nature. Solar power is similar: many square kms of the natural environment must be decked with panels to match our need for energy. Wind is worse. A little physics shows that the energy delivered depends basically on the cube of the wind speed: at low speed its contribution is not very useful; at high speed the turbine must be turned off to prevent its destruction. So not only do wind farms need to cover many square kms but their output responds very unfavourably to fluctuations in wind speed. Indeed, for all these 'renewables' it is the unpredictable variation in output that makes them simply inadequate as large-scale replacements for carbon fuels. On average, they are able to deliver only 20–30% of the designed power, in a largely unpredictable way. Given also the scars they inflict on the environment, and their vulnerability to extreme weather events, they are unsuitable as the main workhorse for energy production. This is especially true as there is an alternative that offers everything required: steady output, high-energy density, resilience and a small environmental footprint – in fact, even better than carbon.

The hardest part is to present the task and its solution in a way that wider society is able to accept

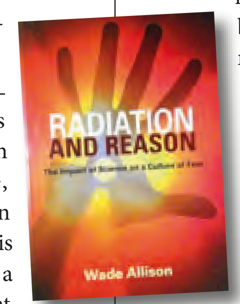
FERMI KINETIC ENERGY

It is quantum mechanics, the de Broglie wave of an electron (mass m) confined in an atom (size L), that sets the energy scale ($h^2/8mL^2$=4eV) of chemistry, electronics, batteries, lasers, etc including the burning of fossil fuels, metabolisation of food and detonation of high explosives.

The same calculation, when applied to a proton or neutron confined in a nucleus, gives a scale of kinetic energy five million times larger – the simple physical factor that has made politicians drunk with power for 70 years! The accessible nuclear energy of Uranium or Thorium fuel, was primed by gravitational collapse in supernovae before the Earth was formed. Unfortunately, few in society welcome what nuclear power has to offer. Some believe nuclear energy to be an unnatural malevolent technology, a nightmare development from the Cold War period; others, though professing ignorance, would simply rather distance themselves from it.

The biggest task here is to reassure the public. In my work I have explored the history, the physics and particularly the basic biology of the effect of radiation and nuclear contamination on life. Undoubtedly, it is the energy source we need – with a safety record and environmental footprint better than any other. Unfortunately, its large potential for energy and the public's ignorance makes it a fertile source of exciting fiction – or rather fact entwined with fiction. There is no doubt that many members of the public at Chernobyl and Fukushima suffered mentally and physically. However, the doses received were so low that it is certain that their symptoms, though real, were caused, not by radiation but by the trauma of being told that they had been irradiated. Real symptoms induced by a falsely-supposed attack is well known to medicine as the Nocebo Effect. In the Placebo Effect a patient is cured of disease when told he has been treated, when he has not. The Nocebo Effect is the malign counterpart[2].

MEDICAL BENEFITS AND PUBLIC OPPROBIUM



It is unfortunate that the public has this negative perception of radiation because, thanks to Marie Curie, moderate and high doses of radiation are used in clinics for cancer diagnosis and treatment, and have been for over a century. Though everyone welcomes that, outside medicine the public expects to be protected from radiation a thousand times weaker. Politicians legislate for this level and, in the event of an accident, authorities evacuate the public from the scene without scientific justification.

Why does nobody say so? I have found that most doctors keep their heads down, anxious to avoid litigation. They prefer to concentrate on their patients' health rather than public policy. Courts of law concern themselves with regulations, not their scientific basis. Industrialists do what is required in a contract – it is not their job to question regulations. Safety professionals are reluctant to undermine their priestly status. Politicians are happy to spend the public's money to appease any public concern, real or imagined, to ensure their re-election. So what people accept is severely coloured by their career and status. As Upton Sinclair wrote: 'It is difficult to get a man to understand something when his salary depends on his not understanding it'.

Maybe as everybody comes to realise how their grandchildren's survival depends on the large-scale adoption of nuclear energy, the message will become more widely welcomed.

Maybe as everybody comes to realise how their grandchildren's survival depends on the large-scale adoption of nuclear energy, the message will become more widely welcomed, not just tolerated. Educating and changing minds takes time, though really we have none to spare.

But what about the hard evidence for the effects of nuclear technology?[3] Physics and biology between them ensure extraordinary levels of safety from both nuclear energy itself and the ionising radiation emitted by radioactivity. I have written two books for a general reader: *Radiation and Reason: the Impact of Science on a Culture of Fear* and *Nuclear is for Life: a Cultural Revolution*[4]. Secondary-level students respond enthusiastically to simple explanations – though such material is carefully avoided in school syllabuses at present.

But many groups in society need to face the science if we are to achieve the revolution required. Avoiding nuclear technology because it is thought to be controversial should be unacceptable: we need to reach the media, schools, government, MPs, the UN – perhaps *you* can help. At the same time the artificial safety regulations that have been blessed by the United Nations need to be changed – beyond most people's game plan, perhaps. However, that is the goal.

Find his book on Amazon at: https://www.amazon.co.uk/Nuclear-Life-Revolution-Wade-Allison/dp/0956275648

1 https://www.project-syndicate.org/commentary/nuclear-energy-clean-green-reliable-by-wade-allison-2019-06

2 www.newscientist.com/article/mg20227081-100-the-science-of-voodoo-when-mind-attacks-body/

3 www.researchgate.net/publication/311175620_Nuclear_energy_and_society_radiation_and_life_-_the_evidence_1

4 www.ypdbooks.com/science-and-technology/1690-wade-allison-special-book-pack-YPD01882.html

DEPARTMENT NEWS & EVENTS

Events... IN PICTURES

PROF BARISH LECTURE (NOBEL LAUREATE)

On 9 July, Prof Barry C Barrish (Caltech, Nobel Prize in Physics, 2017) gave a lecture entitled 'Gravitational waves and prospects for multi-messenger astronomy' to a full house at the Natural History Museum. The talk was followed by a drinks reception.

CHERWELL SIMON MEMORIAL LECTURE

In May, Prof Elena Aprile (Columbia University) delivered the 60th Cherwell Simon Memorial Lecture, entitled 'The XENON project: at the forefront of dark matter detection'.

PHYSICS GARDEN PARTY

The annual garden party took place in June at Wolfson College, hosted by Prof Ian Shipsey. Prof Steven Balbus, a world leader in Black Hole Accretion, delivered a fascinating talk, which was followed by questions and afternoon tea.

NEW CLUB, EDINBURGH

Our first physics alumni event in Scotland took place at the New Club in Edinburgh, in the beautiful Ramsay & Long Rooms on 2 July. The views over Princes Street and the Castle formed the perfect backdrop for drinks and conversation. We'd like to thank Dr Susan Hezlet and Dr William Duncan for their support in organising this wonderful evening.

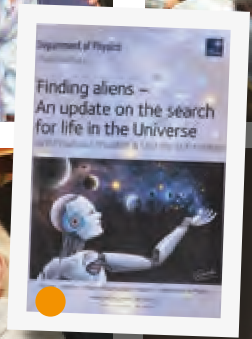
BILL DIAMOND / SETI LECTURE

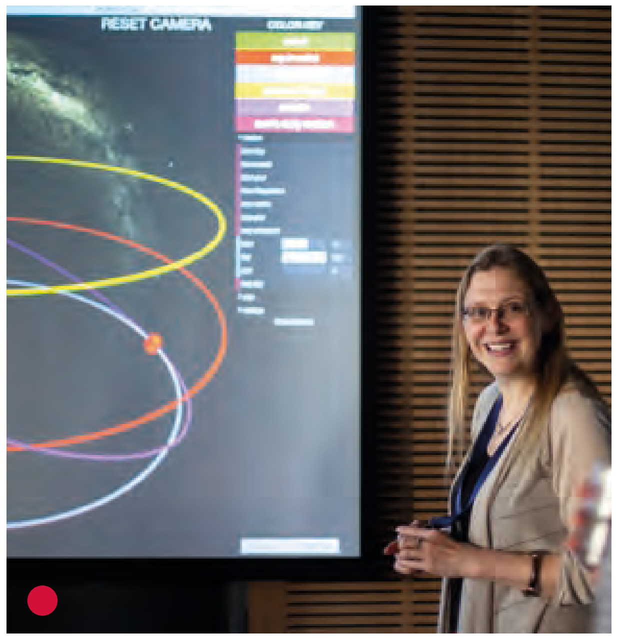
'Finding aliens – An update on the search for life in the Universe' was the special lecture given by Bill Diamond (President & CEO, The SETI Institute) on 6 June. Artist Danielle Futsellar was commissioned to create the artwork for the poster advertising the talk.

THINKING 3D – SPACE & TIME

The Department of Physics and Magdalen College co-hosted this whole day event, part of a year-long series, on 22 June. The event was designed to incite dialogue between artists, historians, mathematicians, astronomers and more. Talks were delivered by Prof Jim Bennett (Early globes, including celestial globes); Mr Peter Bellerby (Challenges of a modern globe-maker); Dr Emma Chapman (Early Universe and Cosmology); Dr Colin Wilson (Observing Venus); Prof Steven Balbus (Black Holes and new methods of observation); Mr Daryl Green (On the work of James Nasmyth and his book on the Moon, published in the 1870s); and Prof Chris Lintott (Citizen science and the Zooniverse). The talks were followed by a drinks and canapés reception.

We are aware that alumni who live far from Oxford would like access to recordings of events. Because of data protection however, not all events can be filmed. Those that can, will be found here: http://podcasts.ox.ac.uk/units/department-physics





IMAGES TOP LEFT, TOP RIGHT AND THIRD ROW MIDDLE © S BEBB. THIRD ROW BOTTOM RIGHT AND FOURTH ROW © JOHN CAIRNS

FORTHCOMING ALUMNI EVENTS

We hold a variety of events throughout the year for our alumni and their guests. All events take place in Oxford, unless otherwise stated. Please visit our website (**www.physics.ox.ac.uk/events**) regularly for latest updates and full details.

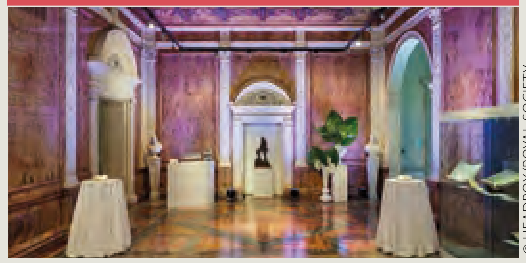
Alumni and their guests are always welcome, and all our events are free, but advance registration is mandatory. If you have any questions about the events, please contact Val Crowder: alumni@physics.ox.ac.uk.

Below is a list of some of the alumni events we have planned for the coming months. We look forward to seeing you soon.

THE 19TH HINTZE LECTURE

14 November, 17:30 *Martin Wood Lecture Theatre*
Prof Heino Falcke: 'The first image of a Black Hole'

AOPP ALUMNI EVENT



© HEADBOX/ROYAL SOCIETY

15 November, 18:30 *Royal Society (London) Kohn Centre*

PARTICLE PHYSICS CHRISTMAS LECTURE

© ICECUBE

7 December, 10:30–16:30 *Martin Wood Lecture Theatre* Prof Francis Halzen

INTERNATIONAL EVENTS

We will be participating in the following international events. More details will follow but please save the date; we'd love you to join us!

MEETING MINDS BERLIN (GERMANY)

March 2020

MEETING MINDS NEW YORK CITY

April 2020

If you have any comments, suggestions or would like to share an idea for an event where you live, please get in touch with Val Crowder, our alumni officer: alumni@physics.ox.ac.uk.

OUTREACH

MAKING PHYSICS ACCESSIBLE FOR ALL

For more information: www.physics.ox.ac.uk/outreachnews

Oxford Physics engages in a series of highly active outreach programmes, which have reached more than 200,000 people over the last five years. Our outreach work is focused in four main areas:

INCREASING ACCESS TO OXORD

Supporting disadvantaged students who have the potential to benefit from study in the department

ENGAGING LOCAL COMMUNITIES

Building partnerships with local communities to enrich the life of the city

INCREASING DIVERSITY IN STEM

Working with children from under-represented backgrounds to raise aspirations

PUBLIC ENGAGEMENT

Supporting our researchers in engaging the public with their research

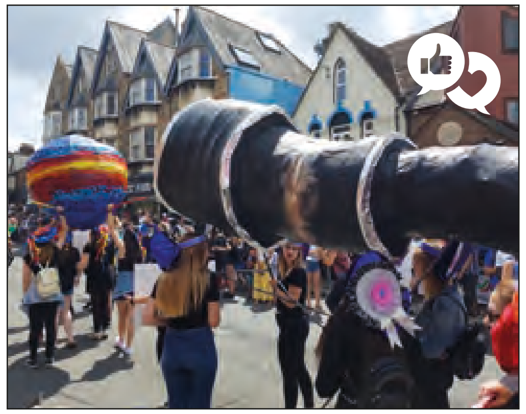
CELEBRATING SCIENCE WITH SPACE-THEMED CARNIVAL

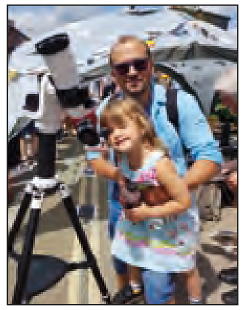
The Cowley Road Carnival takes place every year and regularly attracts 50,000 people. This year's event, which was held on 7 July, had the theme 'Space is the Place' and celebrated the exciting work being carried out by scientists in and around Oxford, as well as commemorating the 50th anniversary of the Moon landing in July 1969.

Researchers worked with young people and community groups in Oxford to design and build colourful creations inspired by our exciting space-related science for this year's carnival, thanks to funding from STFC.

The organiser of the annual carnival, Cowley Road Works, joined forces with the department to connect four local community groups with four groups of Oxford researchers. These groups then worked with artists to create four space-themed carnival structures for the procession. The community groups involved represented a cross-section of people facing barriers to participation in science and who are under-represented within STEM (science, technology, engineering and mathematics) careers.

Researchers also attended the Carnival to join in with the celebrations. Carnival visitors were able to observe the Sun and 'draw the Universe' at the Oxford Physics stall.





Top: Physics-inspired art in the Cowley Road Carnival procession. Bottom left: Passers-by 'draw the Universe'. Bottom right: Carnival visitors observe the Sun through our new solar telescope.

DR BECKY

Dr Becky Smethurst set up a YouTube channel called 'Dr Becky' to engage the public with cutting-edge astrophysics and astronomy research in an accessible and inspiring way. The channel has over 2 million views and 47,000 subscribers. Video topics have included questions such as: 'Should we put telescopes on Mars?' with the most popular video getting over 250,000 views!

- www.youtube.com/drbecky
- @drbecky_
- @drbecky_s

PARTICLE PHYSICS MASTERCLASS FOR A-LEVEL STUDENTS

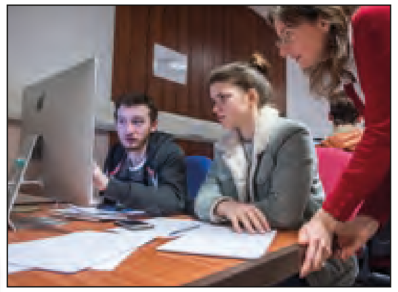
The International Masterclasses in Particle Physics is a programme which allows school students to experience a day working as a particle physicist. We ran two events in March, reaching 40 A-level students.

STUDENTS HAD THE OPPORTUNITY TO:

- LEARN ABOUT PARTICLE PHYSICS FROM CERN RESEARCHERS;
- SEE HOW THE PHYSICS TAUGHT IN THE CLASSROOM IS USED TO CONDUCT EXPERIMENTS PROBING THE MYSTERIES OF THE UNIVERSE;
- ANALYSE REAL DATA FROM THE EXPERIMENTS TO SEARCH FOR SIGNS OF NEW PARTICLES.

We hoped the day helped to inspire the next generation of particle physicists, and plan to run the event again in 2020.

AN AMAZING EXPERIENCE WHICH HAS FURTHERED MY UNDERSTANDING OF PARTICLES. — STUDENT



Above: Students explore particle physics in the undergraduate labs.

HIGGS HUNTERS: CITIZEN SCIENTISTS ANALYSE DATA FROM THE LARGE HADRON COLLIDER

Higgs Hunters, the first particle physics citizen science project in the Zooniverse, has won a Vice Chancellor's Award for Public Engagement with Research. This exciting project was created by Profs Alan Barr and Chris Lintott. It enabled more than 37,000 citizen scientists to play a direct role in the search for new particles by examining data recorded by the ATLAS experiment at the Large Hadron Collider at CERN.

ATLAS datasets record the tracks of particles flying out from the collision of two protons. Usually this is analysed by sophisticated software. The aim of Higgs Hunters was to exploit the human ability to recognise unusual patterns to identify events that could be a sign of an invisible particle – such as a postulated 'baby boson' decaying after travelling away from the beamline.

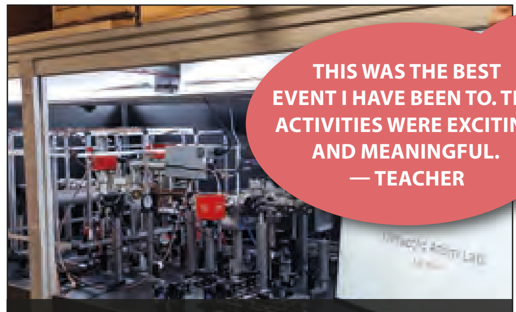
In a partnership between Oxford Physics and the Institute for Research in Schools, the results from the citizen scientists were then examined by school students, who were encouraged to use the data to investigate their own research questions. The students presented research posters at a two-day seminar in Oxford in Summer 2018. The proceedings of this conference have since been submitted for review by colleagues at CERN.

Higgs Hunters has shown the potential for citizen science in particle physics and has built up a community of citizen particle physicists ready for the next challenge.

higgshunters.org

Left: School students present their Higgs Hunters research at Oxford.

QUANTUM 101



THIS WAS THE BEST EVENT I HAVE BEEN TO. THE ACTIVITIES WERE EXCITING AND MEANINGFUL. — TEACHER

Tour of our quantum technologies labs

Quantum 101 was an exciting new opportunity for students, aged 12–15, to explore the weird and wonderful world of quantum physics. Students had the opportunity to work with researchers in the field of quantum physics and explore some of its current and future applications.

A highlight from the day was the opportunity to visit the quantum technology labs in the basement of the department. Students were able to see how researchers are working on the first quantum computers here in Oxford.

- 48 students attended the day from a number of state schools in the South East.
- Over 15 researchers were involved in planning and delivery of the event.

Feedback from students and teachers was very positive and we hope to make this an annual event.

QUANTUM TECHNOLOGY IS LEAPING FORWARDS, AND IT'S TIME WE PUT IT IN THE SPOTLIGHT! IT'S GREAT TO BE ABLE TO WORK WITH YOUNG PHYSICISTS TO INSPIRE AND HELP THEM LEARN ABOUT THIS LESS-UNDERSTOOD AREA OF PHYSICS — DR KATHRYN BOAST, QUANTUM MATERIALS OUTREACH OFFICER

RECORD NUMBERS AT OXFORD PHYSICS OPEN DAYS

1,368 STUDENTS | **20%** INCREASE

We welcomed a record 1,368 prospective students (plus hundreds of parents) to the undergraduate open days over two days in June – an increase of nearly 20% on last year! Visitors attended physics talks, physics and philosophy talks, as well as sessions on the admissions process and the Physics Aptitude Test (PAT), plus tours of the undergraduate laboratory facilities.

www.physics.ox.ac.uk/study-here/undergraduates/open-days

ALUMNI STORIES

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

PROF PAUL D WILLIAMS, LINCOLN 1995, BALLIOL 1999

Atmospheric turbulence research leads to smoother, safer, and cleaner flights

This article tells the story of how we took some basic academic research, dating from my student days at Oxford 20 years ago, and applied it to achieve real-world impacts via improved aviation turbulence forecasts. Atmospheric turbulence is the leading cause of injuries to air travellers and flight attendants. Rough air probably costs the global aviation sector around one billion dollars annually. Furthermore, we know that climate change is causing at least some kinds of turbulence to strengthen.

To help reduce turbulence encounters, we have developed an award-winning turbulence forecasting algorithm, which is now being used operationally by the US National Weather Service. Every day, our algorithm is used in flight planning by commercial and private pilots, flight dispatchers, and air-traffic controllers. To date, our algorithm has improved the comfort, safety, and environmental impact of air travel on billions of passenger journeys, and that figure is growing by several million passenger journeys every day.

But turbulence was not on my mind when I arrived in Oxford for my MPhys degree (Lincoln College, 1995–99), nor even during my graduate studies in the sub-department of Atmospheric, Oceanic and Planetary Physics (Balliol 1999–2003). What was occupying my thoughts during my DPhil, supervised by Peter Read and Tom Haine, was a physical theory for the generation of gravity waves in the atmosphere. These waves can produce clear-air turbulence, which is hazardous to aviation because it is invisible and undetectable by on-board radar.

It was only several years after graduating that I set out to develop the gravity wave theory into a practical turbulence forecasting algorithm. I achieved this by collaborating with John Knox (University of Georgia, USA) and Don McCann (McCann Aviation Weather Research, Inc., USA). Our forecasting method works by analysing the atmospheric wind field and using a set of equations to identify the regions where the geostrophic balance (between the Coriolis force and the horizontal pressure gradient force) is breaking down. The subsequent loss of balance generates gravity waves, leading to shear instabilities and the production of turbulence.

INITIAL TESTS

After I left Oxford to take up my position at the University of Reading, we conducted some initial tests on the accuracy of our forecasting algorithm, with promising results. At that time, the US Federal Government's goals for aviation turbulence forecasting were not being achieved, either by automated systems or experienced human forecasters, but our algorithm came tantalisingly close. We published our results in 2008, concluding that 'major improvements in clear-air turbulence forecasting could result if the methods presented herein become operational'.

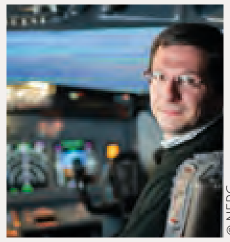
It is crucial that we improve turbulence forecasts, because rough air has long plagued the global aviation sector. Tens of thousands of aircraft annually encounter turbulence strong enough to throw unsecured objects and people around inside the cabin. On scheduled commercial flights involving large airliners, official statistics indicate that several hundred passengers and flight attendants are injured every year, but we know this is just the tip of the iceberg and the real injury rate is probably in the thousands. A typical airline loses 7,000 working days annually due to flight attendants being injured by turbulence and unable to work. On smaller planes, turbulence causes around 40 fatalities each year in the USA alone.

At its worst, turbulence can cause structural damage to aircraft. For example, a plane flying over Colorado on 9 December 1992 encountered extreme clear-air turbulence, which tore off about six metres of its left wing and one of its four engines. For all the above reasons, turbulence is the underlying cause of many people's fear of flying. This fear reportedly affects up to 40% of the population, and it is classified as a specific phobia in the Diagnostic and Statistical Manual of Mental Disorders. Most people find it generally unpleasant and uncomfortable to be randomly buffeted up and down by turbulence, but for the unfortunate sufferers of aviophobia, even light turbulence can be extremely distressing.

CLIMATE CHANGE

But there's another chapter to this story. Turbulence also has consequences for the environment, by causing excessive fuel consumption and CO_2 emissions. Up to two-thirds of flights deviate from the most fuel-efficient altitude due to turbulence. This wastes fuel – up to 160 million gallons annually in the USA – and it also contributes to climate change through 1.5 million tonnes of unnecessary CO_2 emissions annually. At a time when we're all concerned about lowering aviation's carbon footprint, improving turbulence forecasts may be a relatively easy way to help make flying greener.

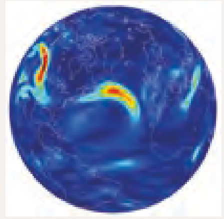
Furthermore, climate change is expected to make turbulence much worse in future. In particular, our published projections indicate that there will be several hundred per cent more clear-air turbulence globally by 2050–80. The increase occurs because climate change strengthens the vertical wind shear in the jet stream at flight cruising altitudes – and our recent *Nature* paper shows that the shear has already increased by 15% in the North Atlantic region since satellites began monitoring the jet stream in the 1970s. These findings underline the increasingly urgent need to develop better aviation turbulence forecasting techniques.



© NERC

Paul Williams in the cockpit of an aircraft, with the weather radar on the flight deck visible in the background.

@DrPaulDWilliams



© PAUL WILLIAMS

A patch of clear-air turbulence in the jet stream over the North Atlantic Ocean, calculated using supercomputer simulations of the global atmospheric circulation.

AT A TIME WHEN WE'RE ALL CONCERNED ABOUT LOWERING AVIATION'S CARBON FOOTPRINT, IMPROVING TURBULENCE FORECASTS MAY BE A RELATIVELY EASY WAY TO HELP MAKE FLYING GREENER.

The operational challenges associated with turbulence are compounded by the projected future growth of the aviation sector. Historically, global air traffic (measured in passenger-kilometres) has experienced an average long-term growth rate of 5% per year, which corresponds to a doubling period of about 14 years. According to Boeing's market outlook, this trend is expected to continue for at least the next 20 years. Accurate turbulence forecasts are needed to ensure the efficient use of airspace in our increasingly crowded skies.

SMOOTHER JOURNEYS AHEAD

Future passenger growth coupled with climate change will lead to more turbulence encounters, all other things being equal. Therefore, it is good news for air travellers that our improved turbulence forecasting algorithm is now being used operationally by the Aviation Weather Center (AWC) in the National Weather Service (NWS), which is the US equivalent of the Met Office. The turbulence forecasts are freely available via an official US government website (www.aviationweather.gov/turbulence/gtg). They forecast turbulence up to 18 hours ahead, updated hourly. Our algorithm is the latest in a basket of diagnostics that are optimally combined to produce the final published forecast.

Every day since 20 October 2015, turbulence forecasts made with our algorithm have been used in flight planning by commercial and private pilots, flight dispatchers, and air-traffic controllers. The aviation sector is benefitting from advance knowledge of the locations of turbulence, with greater accuracy than ever before, allowing flight routes through smooth air to be planned. The United States was a natural place to test and roll out the algorithm, because it has arguably the most extensive air transportation network in the world. On an average day in the US, 2.6 million people fly on a scheduled passenger service. To date, therefore, our algorithm has improved the comfort and safety of air travel on nearly four billion passenger journeys.

Our turbulence forecasting algorithm has won several awards recently, including £5,000 in the Natural Environment Research Council (NERC) Impact Awards last year. But the real prize is the knowledge that the algorithm is making a difference to people's lives every day. In the time it has taken you to read this article, thousands of passengers have taken to the skies and are benefitting from our research. It is the perfect and somewhat unexpected culmination of a DPhil research project that began in earnest at Oxford 20 years ago.

© UNIVERSITY OF READING

Paul Williams at Heathrow Airport, as a British Airways aircraft departs through partly cloudy skies.

NICK ARMSTRONG MA CPHYS MINSTP, WADHAM 1979–82

Wadham's Scottish Physics Cycle

My first-year tutor in Physics at Wadham made a distinct impression on me. His name was Don Edmonds and he was relaxed, friendly, approachable and with no distinct accent to bely his roots (unlike mine!) His enjoyment of physics was obvious and I remember he spent a lot of time working on cobwebs simply because he thought it was fun. He had a standard saying for solving problems: 'Turn the handle and out pops the answer.' I personally found it didn't actually always work for me! But at least the saying always stayed with me and because of it, I've regularly thought about him.

A few years after graduating, I also switched into teaching and eventually moved to Edinburgh to become the Head of Physics at the Edinburgh Academy. This school is the Alma Mater of James Clerk Maxwell and the school embraced his legacy. It felt like an appropriate place for a physicist to be. Very shortly after moving, my wife recounted a conversation she had had that day with another lady at a toddler group when they were alternately sending the kids down the chute (that's what a slide is called in Scotland!) In the type of 'part sentence' conversation with which only adults looking after kids can identify, it was discovered that the lady was Don Edmonds' daughter. Her two older boys attended the Academy and I got to teach them both. We loved the story.

However, in my first year of teaching there, another student came immediately to attention. The A level class had some smart students in it and one in fact went on to work for NASA. It was another though, that stood out from the rest – simply for being an extremely intelligent and studious young man. This didn't make him an introvert. In fact, I remember him being very good at violin as well as physics. Neither was he 'cocky'. He knew he was good but he didn't show off. We both knew he could easily have put me on the spot asking me questions in class that I couldn't answer but he was far too polite to ever do so. He represented Britain in the World Physics Olympiad in Iceland and came 15th. I remember always marking his homework first so that I knew I had the right answer before I marked the rest and it was a shame, I didn't get to find out what happened to him after Further Education.

Keeping in touch with Wadham and its Alumni has many benefits. One of them has been that through the Wadham College Gazette, for example, I discovered that this exceptional pupil, Martin Shotter, had become a Physics tutor at Wadham. For me, this has completed a cycle of personal connections to impressive Scottish physicists having links with Wadham. I shall always keep in touch!

WIKIPEDIA.ORG

THE SAVILIAN CHAIR IN ASTRONOMY IN MODERN TIMES

Prof Steven Balbus

© NASA/DANA BERRY

Since its inception in 1619, the holders of the Savilian Chair in Astronomy have inevitably reflected the contemporaneous developments of astronomy. Early seventeenth-century astronomy was dominated by giants like Johannes Kepler and Galileo Galilei. It was a time when the precise mathematical description of the solar system was taking form, and it would have been impossible to have been an astronomer of any influence at any interval of this century without considerable expertise in mathematics. The mathematical contributions of Sir Christopher Wren, the most distinguished holder of this Chair, were of a standard high enough to attract an enthusiastic endorsement from no less than Isaac Newton himself. He was not someone known for his fulsome praise.

As telescopes and astronomy both grew in sophistication, astronomy expanded beyond the solar system, becoming more concerned with stars and their precise positions. 'The law of the stars' is, in fact, the Greek etymology of the word astronomy. We see the same stellar focus in the eighteenth and nineteenth century holders of the Savilian Chair. It wasn't until the nineteenth century that it became possible to directly measure the distances to nearby stars using a technique known as trigonometric parallax, a form of triangulation using the Earth's orbital diameter as a baseline. Before this, however, the change in coordinate position of a star on the celestial sphere could be determined with sufficient precision that James Bradley, a distinguished eighteenth-century occupant of the Chair, could use these position measurements to determine the velocity of light! Bradley is known for his explanation (and exploitation) of the aberration of starlight. This is an effect whereby the positions of stars appear to change in the sky by tiny amounts, not because of the orbital displacement of the Earth, but because our instantaneous orbital velocity changes the apparent path of the light from the distant star. Bradley's method yielded an accurate value for the speed of light.

STEPPING INTO THE 20TH CENTURY

Crossing into the twentieth century, the Savilian Chair was held by Herbert Turner, a polymath, Second Wrangler in his Cambridge Tripos mathematics exam, and an astrophysicist with an avid interest in geophysics. Turner continued the Savilian tradition of accurate stellar position measurements, devising ingenious, effort-saving calculational methods. But he also brought Oxford geoscience firmly into the twentieth century, as one of the first researchers to put forth the notion of a liquid core at the Earth's centre. This is now known to be true for the outer mantle of an otherwise solid core. He also originated the concept of deep-focus earthquakes, seismic tremors now associated with tectonic plate boundaries, which originate more than 300km below the Earth's surface.

The arrival of Henry Plaskett to the Savilian post in 1932, following the death of Turner two years earlier, marks the ascension of solar physics at Oxford. Plaskett, together with his successor Donald Blackwell (1960), were prominent astronomical spectroscopists. This field involves the detailed study of the spectrum of starlight, namely how much energy is seen to be radiated at different wavelengths. Solar spectroscopy was a mid-twentieth-century field of considerable astronomical interest. Up until the 1930s, astronomers still did not know, even crudely, what elements were most abundant in stars. A detailed understanding of the Sun's spectrum, a representative star we can study in far greater detail than any other, was key to solving this puzzle. The solar spectrum revealed the same relative percentages of carbon, silicon, and common elements of the Earth's crust that are actually measured on the planet. The conclusion drawn was that the Sun was made of the same stuff as the Earth. But the physics details of when one can actually see an atom of a particular element in a star's atmosphere, and when one cannot, are crucial to a correct interpretation. It is to Celia Payne-Gaposhkin, who in her remarkable 1923 doctoral thesis at Radcliffe College (now part of Harvard University) showed that the Sun is comprised almost entirely of hydrogen and helium, that we owe our fundamental understanding of the composition of the Universe. Plaskett and Blackwell continued this spectroscopic tradition throughout most of the twentieth century, developing techniques for interpreting the spectra of the Sun and many other stars in our Galaxy, determining the precise physical conditions in their atmospheres as well as precise elemental abundances.

A NEW ERA IN ASTRONOMY

By the time Blackwell retired from the Savilian Chair in 1988, the field of astronomy had utterly changed. The stunning discoveries of the radiation left over from the creation of the Universe (the 'Big Bang'), of pulsars, of galaxies that gush radio waves, of X-ray 'stars', of dark matter that dominates the gravitational forces of galaxies, together with the brilliant analyses of Roger Penrose and Stephen Hawking that brought black holes to life – all of these permanently changed the priorities of astronomy. A very new kind of Savilian Professor was called for.

In 1988 George Efstathiou turned thirty-three, an exceptionally young age (by modern standards) to assume a senior chair like the Savilian. George already had made a name for himself by his work in cosmology, in particular for his masterful computations of the structure on the largest scales of the Universe. He would go on to be one of the world's leading cosmologists, responsible, with his co-workers, for our current understanding of how the intricate formation patterns of clusters and superclusters of galaxies evolve from small initial seeds, and to be a leading authority in the interpretation of the physics of the early Universe gleaned from study of the radiation from the Big Bang.

Lured away by Cambridge in 1997, George was succeeded by Joseph Silk in 1999. Joe was (and is!) an eminent and prolific cosmologist. But Joe's interests spanned almost all of theoretical astrophysics, from the nature of the gaseous medium between the stars, to star and galaxy formation, to the physics of dark matter and exotic astroparticles. Joe was the first theorist to point out, in 1968, that the cosmic background radiation played a crucial role in constraining the growth of structures able to detach and collapse from the expanding background medium of the Universe. 'Silk damping' and the 'Silk mass' have become part of the cosmological lexicon.

Thus, when in 2012 I had a chance to follow George and Joe in the Savilian Chair, I was both flattered and daunted. Like Joe, my interests are broad. I have worked on understanding cool gas orbiting in galaxies and orbiting around forming stars, and on the very hot, X-ray emitting gas that sits between galaxies and emits X-rays. I have worked on the internal rotation of stars, trying to understand why the Sun displays such a very unusual dynamical behaviour. I suspect my colleagues would identify me most closely for work that I did with my associate John Hawley in the 1990s on a puzzle known as the angular momentum problem. Just as a figure skater spins rapidly when she pulls in her arms and legs tightly, a body of gas trying to form a star, or to fall into a black hole, encounters a severe problem: rapid rotation prevents the ultimate collapse onto the central object. There is too much angular momentum. John and I showed that including magnetic effects renders the infalling gas turbulent, and that the excess angular momentum can be transported outward via this process through the gaseous medium itself, allowing 'accretion' (as it is called) to proceed. This breakdown into turbulence is critical for the formation of a wide range of astrophysical objects, and is the basis for the computer simulations used for understanding the wonderful black hole image produced by the Event Horizon Telescope which captured the public imagination earlier this year.

Modesty forbids further self-indulgence, but I would like to think that both the Savilian Chairs of Astronomy and Geometry continue to be sources of pride for the college and of inspiration for its students. I am most fortunate to be in post for this 400th anniversary celebration, to share this time with my dual Savilian Professor of Geometry, Frances Kirwan, to have had an opportunity to review the remarkable accomplishments of my predecessors, and to have been able to address an eager and engaged public on several occasions.

Thank you so much, Will Poole and Daryl Green, the Fellow Librarians of New and Magdalen Colleges respectively, for your generous encouragement and sage advice throughout this exciting year. My one regret is that, barring an as yet to be acquired ability to alter the local spacetime geometry of the Universe, neither Frances nor I shall be present to enjoy the 500th anniversary celebrations of the Savilian Chairs in 2119. More's the pity.

L–R: Sir Henry Savile (1549–1622) was an English scholar and mathematician, Warden of Merton College, Oxford, and Provost of Eton. He endowed the Savilian Chairs of Astronomy and of Geometry at Oxford University.

Sir Christopher Wren PRS FRS (1632–1723) was an English anatomist, astronomer and mathematician-physicist, as well as one of the most highly acclaimed English architects in history. Educated in Latin and Aristotelian physics in Wadham College, and later fellow of All Soul's College, he was also founder of the Royal Society. In 1661, Wren was elected Savilian Professor of Astronomy at Oxford.

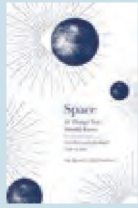
James Bradley FRS (1693–1762) was an English astronomer and priest, who entered Balliol College in 1711. In 1721 he was appointed to the Savilian chair of astronomy at Oxford, and in 1742, he succeeded Edmond Halley as Astronomer Royal.

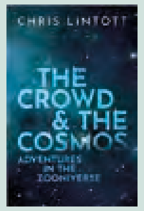
THIS PIECE APPEARED IN *GEOMETRY AND ASTRONOMY IN NEW COLLEGE, OXFORD: ON THE QUATERCENTENARY OF THE SAVILIAN PROFESSORSHIPS, 1619–2019* (NEW COLLEGE, 2019). WITH THE PERMISSION OF NEW COLLEGE LIBRARY.

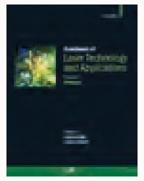
PEOPLE

BOOKS BY OUR ACADEMICS

We are often asked about new books written by members of the Department. Here is a compilation of some of them…

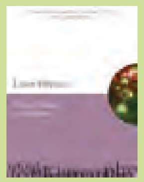
Space: 10 Things You Should Know

DR BECKY SMETHURST
Orion and Seven Dials
Ten captivating, simple essays that guide you swiftly through the galaxies, explaining the mysteries of black holes, dark matter and what existed before the Big Bang. Presenting the evidence as to whether we really are alone, illuminating what we still don't know, and much more besides.
youtube.com/drbecky
@drbecky_s @drbecky_

The Crowd and the Cosmos

PROF CHRIS LINTOTT
Oxford University Press
Find out how you can help astronomers find planets – and count penguins.
Requests for talks via: **crowdandcosmos.com**
@chrislintott

Handbook of Laser Technology & Applications

ED: PROF COLIN E WEBB MBE FRS AND JULIAN JONES
Originally published by the Institute of Physics Press, but now available from CRC Taylor and Francis
Three-volume set: Laser Components, Properties, and Basic Principles.

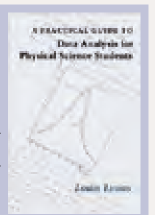
Jet Stream: A Journey through our Changing Climate

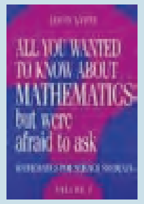
DR TIM WOOLINGS
Oxford University Press
A fascinating introduction to the jet stream, providing insight into how it affects our weather, and how it relates to extreme weather events.
@TimWoollings

Laser Physics

PROFS COLIN WEBB & SIMON HOOKER
Oxford University Press
An undergraduate and first year graduate text book on Laser Physics, part of the Oxford Master Series in Atomic, Optical, and Laser Physics.

Statistics for nuclear and particle physicists

PROF LOUIS LYONS
Cambridge University Press
Practical statistics techniques that are used in data analyses in particle and nuclear physics, and other nearby fields (eg useful distributions; parameter fitting; hypotheses testing; Monte Carlo simulation etc).

A Practical Guide to Data Analysis for Physical Science Students

PROF LOUIS LYONS
Cambridge University Press
Explaining to first year undergraduates how to calculate uncertainties on measured physical quantities; and understanding straight line fitting. Also available in Japanese.

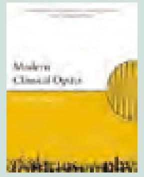
All you wanted to know about mathematics but were afraid to ask

PROF LOUIS LYONS
Cambridge University Press
2 Volumes. Explaining the mathematical techniques that form part of first and second year undergraduate courses in Physics, Engineering, Chemistry etc.

Trinity – The Treachery and Pursuit of the Most Dangerous Spy in History

PROF FRANK CLOSE
Allen Lane
The story of Oxford Professor Rudolf Peierls (father of the atomic bomb), his intellectual son, the atom spy Klaus Fuchs, and the ghosts of the security services trying to decide which of them was the spy. Also gives the science behind what Fuchs passed to the Russians.
@closefrank

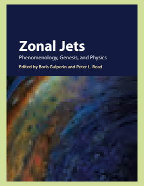
The Future of Fusion Energy

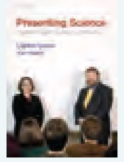
PROF JUSTIN BALL & JASON PARISI
World Scientific Europe
Popular science book that helps general public and scientists to understand the past, present and future of fusion energy research.
@JB_Fusion

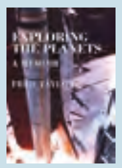
Modern Classical Optics

PROF GEOFFREY BROOKER
Oxford University Press
A title in OUP's Master Series, aimed at the fourth year MPhys course.

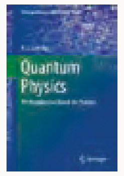
Science and Humanity – a Humane Philosophy of Science and Religion

PROF ANDREW STEANE
Oxford University Press
Reconfigures the public understanding of science by bringing in mainstream philosophy of science.

Zonal Jets – Phenomenology, Genesis and Physics

PROF PETER READ [EDS. BORIS GALPERIN & PETER READ]
Cambridge University Press
Everything you wanted to know about zonal jets in atmospheres, oceans, planetary interiors and magnetised plasmas, in nature and the laboratory, but were afraid to ask!

Presenting Science: A practical guide to giving a good talk

PROFS ÇIGDEM IŞSEVER AND KEN PEACH
Oxford University Press
'Giving a talk' is one of the most important ways in which we communicate our research, and this book covers everything from a ten-minute briefing to a handful of colleagues, to a keynote address to a major international conference, with the aim of getting the message across.

Exploring the Planets – A Memoir

PROF FRED TAYLOR
Oxford University Press
Personal history and anecdotes of a career mainly in Oxford Physics, 1966 to 2016.

Quantum Physics: An Introduction Based on Photons

PROF ALEXANDER LVOVSKY
Springer
An undergraduate textbook that teaches quantum physics in a 'reverse' way: first entanglement, then wavefunctions. Now also published in Russian.

Do you have a photo from your time in Oxford? A story or anecdote that you would like to share?

The alumni office is making the archives more accessible and interactive. Send your contributions, no matter how big or small, to Val Crowder, Alumni Officer: **alumni@physics.ox.ac.uk**

Would you like to host an event for physics alumni?

It could be a drinks reception or dinner, a visit to your company for a small or large group… the possibilities are endless. Please get in touch for an informal conversation, we'd love to hear from you!

Email Val Crowder, Alumni Officer: **alumni@physics.ox.ac.uk**

REGISTER FOR ALUMNI NEWS & EVENT UPDATES AT www.physics.ox.ac.uk/alumni/connect

Congratulations to all our colleagues who were recognised in the 2019 Vice Chancellor's Public Engagement with Research Awards. **Prof Alan Barr** (@higgshunters) in collaboration with **Prof Chris Lintott** (@chrislintott); **Dr Becky Smethurst** (@drbecky_) and **Dr Sam Henry** (@7vdj).

COMINGS, GOINGS & AWARDS...

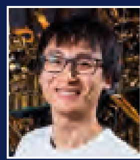
COMINGS...

Name	Position	Department
Prof David Alonso	Associate Professor	Astrophysics
Dr James Kariuki	Mechanical Design Engineer	Central Physics

GOINGS...

Name	Position	Department
Mr Kirk Arndt	Silicon Detector Development Engineer	Particle Physics
Mr Neil Clifford	Senior Systems Manager	Central Physics
Dr Kerri Donaldson Hanna	UKSA Fellow	AOPP
Dr Rick Hamilton	Senior Research Assistant	CMP
Prof Cigdem Issever	Physics Senior Lecturer	Particle Physics
Mr Kashif Mohammad	Linux Systems Manager	Particle Physics
Mrs Louise Sumner	Head of Student Administration	Central Physics
Prof Laure Zanna	Associate Professor of Physical Climate Science	AOPP

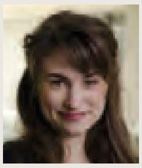
Prof Achillefs Kapanidis and Mr Bo Jing (Condensed Matter Physics) have been named as BBSRC's Innovator of the year 2019 – an award celebrating excellent research which demonstrates impact. Read more about the award: https://oni.bio/



The Galaxy Zoo Team (Astrophysics) was awarded the 2019 Royal Astronomical Society Award for Group Achievement, for contributing significantly to our knowledge of the formation and evolution of galaxies, through strong commitment to collaboration with members of the public.

AWARDS...

Prof Katherine Blundell OBE (Astrophysics) was appointed Gresham Professor of Astronomy. In this capacity, Prof Blundell will continue the 421-year-old tradition of delivering free lectures aimed at the public within the City of London and beyond. www.gresham.ac.uk/professorships/astronomy-professorship.



Dr Megan Engel was awarded the Schmidt Science Fellowship. Megan aims to gain expertise in machine learning techniques to build algorithms that can map the self-assembly process with unprecedented accuracy. More information about the fellowship can be found here: schmidtsciencefellows.org.

Dr Roger Johnson (Quantum Materials/Condensed Matter Physics) was awarded the BTM Willis prize for his work on the understanding of magnetic and magnetoelectric phenomena achieved through state-of-the-art structural studies of complex crystalline solids. The prize is jointly awarded by the IoP and the RSC to an early career researcher.

Dr Xianguo Lu (Particle Physics) was awarded the 2019 STFC Ernest Rutherford Fellowship, to undertake research on Neutrino interactions in the GeV regime.

Prof Ian Shipsey (Particle Physics; Henry Moseley Centenary Professor of Physics and HOD) was awarded the Institute of Physics 2019 Chadwick Medal and Prize for his elucidation of the physics of heavy quarks, the development of the enabling instrumentation, and leadership of scientific collaborations.

Prof Alexander Schekochihin has been awarded the Institute of Physics 2019 Cecelia Payne-Gaposchkin Medal and Prize for elucidating the dynamics that regulate the properties of turbulent, magnetised laboratory and astrophysical plasmas.

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We hope you enjoyed reading this issue of the Physics Department's Newsletter. To contact the Newsletter editor, Prof Dimitra Rigopoulou, please email **newsletter@physics.ox.ac.uk**. For latest news on developments at the Oxford Physics Department, see **www.physics.ox.ac.uk**. To contact the alumni office, email **alumni@physics.ox.ac.uk**. For events and lectures, **www.physics.ox.ac.uk/events**.