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Department of Physics Newsletter

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EXOPLANETS:
WHERE THE WILD THINGS ARE

Prof Ray Pierrehumbert, Halley Professor of Physics

Sometime in the 1590s, early in the wake of the Copernican revolution, the Dominican friar Giordano Bruno proposed that the stars were Suns like our own, that had their own worlds circling them – perhaps even inhabited by beings like (or perhaps not like) us. In scientific circles, it is widely believed that poor Giordano was martyred for his radical ideas about exoplanets, but in fact Copernicanism and its further ramifications was not considered heretical by the Church at the time, and it was probably his more overtly heretical ideas that got him into trouble with the Inquisition. Be that as it may, it took about 400 years from Bruno's time before the first exoplanet discovery was confirmed, in 1992, with the discovery of a system of planets orbiting a millisecond pulsar. This was followed not long after by the discovery in 1995 of a planet orbiting a main sequence star (i.e. of the same family of hydrogen-burning stars as our Sun), 51 Pegasi. Since then, the floodgates opened, and we now know of more than 3500 worlds circling stars other than our own.

Oxford is at the forefront of the exoplanet revolution, with leading-edge work on detection and characterisation of exoplanets and their atmospheres, and both theoretical and computational exploration of their possible climates, taking place in the Astrophysics and Atmospheric Oceanic and Planetary Physics (AOPP) subdepartments and blurring the boundaries between the two. This builds on a long tradition of exploration of Solar System planets by faculty of the Physics Department. Further, because atmospheres are dynamic entities interacting geochemically with the crust and hot interiors of rocky planets, exoplanets engage problems of interest to our colleagues in Earth Sciences as well; some of these points of contact are explored in my recent Lobanov-Rostovsky lecture, available online at https://www.alumniweb.ox.ac.uk/earth/lobanov-rostovsky-lecture. There will be further opportunities to learn about Oxford's work on planetary and exoplanetary science at the alumni event the Physics Department will be running at the Royal Society on 11 November 2016. Details can be found in the event listings at www.physics.ox.ac.uk.

HOW TO FIND AN EXOPLANET

There are two chief means of detecting exoplanets and characterising their orbits. Because stars are much more massive than planets, to a first approximation a planet orbits around the centre of its star. To be more precise though, the star and planet both orbit about their common centre of mass, which is slightly offset from the centre of the star. This slight offset causes the star to wobble a bit as the planet proceeds in its orbit, so as seen from an Earth observer, sometimes the star is moving towards the observer, and sometimes away. This tiny velocity, which is not much more than a swift jogging pace, can be detected through the Doppler shift of light from the star – the light looks a tiny bit more blue when the star is moving towards the Earth, and a tiny bit more red when the star is moving away. This technique for detecting exoplanets has been known for a century or more, but it was not until the 1990s that technological improvements in spectroscopic instrumentation made the implementation of the programme possible. The first exoplanets were discovered by this method, known as the Radial Velocity (RV) method. The RV method gives the period of a planet's orbit, and using undergraduate-level Newtonian mechanics one can then determine the distance of the planet from its star. Astrophysical techniques tell us the power output (luminosity) of the star, and from there one can estimate the temperature of the planet, contingent on what kind of atmosphere it might have. Thus begins exoclimate dynamics. The RV technique also provides a lower bound on the mass of the planet. Our nearest exoplanet, Proxima Centauri b, a mere 4.6 light years distant, was detected by the RV technique. RV detections are generally done using ground-based telescopes.

The other major technique for detecting exoplanets is the Transit Method. When a planet passes in front of its star, the light from the star is very slightly dimmed. All planets transit when seen from the right position, but if you are an observer stuck in just one place, like the Solar System, things have to be lined up just right for a planet to transit. Fortunately, even though the chance of any given system transiting as seen from Earth is very small (typically under one per cent), there are millions of stars with planets within detection range, so a large number of planets have been captured by the transit method. If the size of the star is known (something astrophysics tells us with pretty good accuracy) then the amount of dimming of the star tells us the size of the planet – as opposed to its mass. A bigger planet blocks more of the starlight and leads to more dimming. Transit observations also yield the period of the orbit, and hence the distance of the planet from the star, though they provide less indication of the shape of the orbit (i.e. how elliptical vs circular) than the RV method. When it is possible to observe a system with both the transit and RV method, then as a planet hunter you've really hit the jackpot, since the two methods together turn the RV lower bound on mass into a tight mass estimate. With this, in conjunction with the size data from the transit depth, you know the density of the planet – and therefore something about what it is made of. Even without RV observations, transit observations of systems with multiple planets (and there are many such systems known) can provide mass and density estimates through a technique called Transit Time Variation (TTV). The gravitational tugging of one planet on another yields subtle variations of the times during which transits occur, from which it is possible to back out the mass of the planets.

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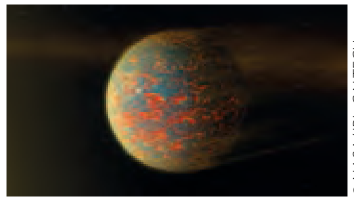
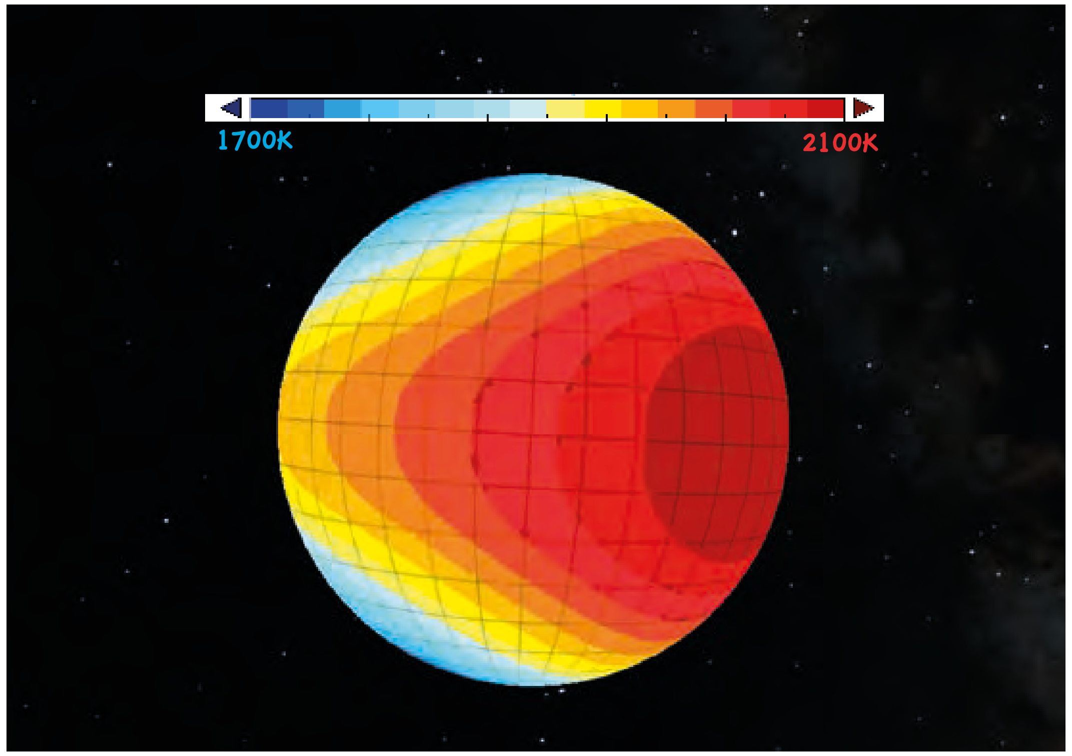
SEARCHING FOR ATMOSPHERES

Transit methods also provide our main window into the composition – or even existence – of exoplanet atmospheres. An atmosphere gradually peters out into vacuum with distance from a planet's centre. Each gas that may be present in an atmosphere (e.g. water vapour) is more opaque at some wavelengths of starlight being blocked than at others. Thus, in transit observations, the planet looks a bit bigger at wavelengths where the gases in the atmosphere are good absorbers than at wavelengths where all the gases are fairly transparent. This can be used as a kind of planet-sized spectroscope to determine what gases are in the atmosphere. Unfortunately, our near neighbor Proxima Centauri b does not transit, and so is not amenable to atmospheric characterisation in this way. For planets that are not transiting, it is sometimes still possible to get information about the character of the atmosphere by looking at how the infrared emission varies as the planet proceeds through its orbit, presenting different geographical regions to the telescope at different points of the orbit. This can tell us the difference between the dayside and nightside temperature of a planet, and thus give information about how well the atmosphere (if any) transports heat from the illuminated to the dark parts of the planet. The technique works especially well



Cover image: Artist's impression of the hot, rocky exoplanet called 55 Cancri e, which is nearly two times as wide as Earth. Data from NASA's Spitzer Space Telescope show that the planet has extreme temperature swings and a possible reason for this might be the presence of lava pools.



Simulation of the radiating temperature of the planet 55 Cnc-e, assuming a hydrogen atmosphere and high-level cloud that is a good absorber of incoming stellar radiation. Results are shown on a globe, and the view is as would be seen looking at the planet with one's back to the star. Radiating temperature is the temperature that would be seen by an infrared telescope, and provides an indication of how well a planet's atmosphere redistributes heat. For a planet without an atmosphere, the hot spot would be at the centre of the globe, as seen from this angle.

On the naming of exoplanets

So far, exoplanets have not been given names like the names assigned to Solar System planets, satellites and even asteroids. There are too many of them, and the discoveries are coming too fast for the usual naming apparatus to keep up. Actually, the situation is not very different for stars themselves. Most stars just have a catalogue number (sometimes several different catalogue numbers), and it is only a few favourites like Betelgeuse or Aldebaran or Alpha Centauri that have names. A typical catalogue number for a star is GJ581, which is a red dwarf star positioned in the constellation Libra (though not visible to the naked eye).

Once exoplanets started to be discovered, the lower class letter 'a' was appended to the catalogue entry to designate the star, e.g. GJ581a. Planets are then designated in order of discovery, starting from 'b,' so GJ581b is the first planet detected about the star GJ581a, and so forth. When the star itself has a name, that is used in place of the catalogue number of the star – thus Proxima Centauri b is the first planet discovered around the star Proxima Centauri. To make life even more complicated, many planets have been found around double and even triple star systems; in such cases, when the individual stars do not have names, the stars are designated by capital letters and the planets (as before) by lower case letters. Thus the planet 55 CancriA-e (one of my favourites!) is the fourth planet discovered orbiting the star 55 CancriA, which in turn is the first star discovered in the binary system 55 Cancri. Since there aren't any planets known (yet) around 55CancriB, we often just say 55 Cancri-e for short.

To avoid having to rename planets as new ones are discovered in a given system, the planets are lettered in order of discovery, regardless of their ordering in distance from the star. Sometimes detections turn out to be false positives, but in such cases later discoveries retain their original letters. Astronomers work hard to avoid this situation, and most of the disappearing planets date back to earlier days of the subject. These days, tentative detections are usually designated 'objects of interest' with their own catalogue number, rather like a 'person of interest' in an Inspector Morse mystery. It is only after meticulous cross-checking that they are admitted into the fold as confirmed planets with a planetary catalogue number.

for planets much hotter than Earth, since hot planets (indeed any hot objects) radiate more energy.

Oxford is at the forefront of efforts to characterize exoplanet atmospheres. For example, Suzanne Aigrain's group in Astrophysics has used transit depth spectra to characterize clouds on extrasolar gas giant planets. They are also developing techniques to make use of the revolutionary data that will be coming in from the James Webb Space Telescope. In many astrophysics departments, the radiative transfer needed to retrieve atmospheric characteristics from astronomical observations needs to be farmed out to some other institution, but at Oxford we can do it all at home, because of productive collaboration with Pat Irwin's retrieval group in AOPP. This is a great example of the unity of physics, as the retrievals rest on fundamentals of quantum theory and spectroscopy, and there are deep connections between the way these fundamentals are used for satellite retrievals of Earth's atmosphere, for observation of Solar System planets, and for exoplanets.

WILD NEW WORLDS

So what have we found so far in this zoo of new worlds? In short, a lot of things that have no counterpart in our Solar System, that challenge our very views of what planets are like, and which require real out-of-the box thinking about planetary climate. These include Hot Jupiters – gas giants like our cold Jupiter, but in such close orbits that even their outer atmospheres have temperatures of thousands of degrees K. On such planets, clouds are made of things (like sapphire, or more prosaically, corundum) which are thought of as minerals on Earth. A rock is just ice by another name.

There are planets that are tide-locked to their stars, like the Moon is tide-locked to Earth, so that they have a permanent dayside and a permanent nightside. Some of these, like 55 CancriA-e, are so hot that the dayside should have a permanent magma ocean. It is thought that such magma oceans (like the lava lakes you see inside volcanos on Earth) should outgas a thin sodium vapour atmosphere but – surprise – recent astronomical observations indicate that the planet has a thick heat-transporting atmosphere, which may even be dominated by hydrogen (which really should not be there, since on such a planet light gases should escape rapidly to space). And so, I have been modelling what the planet would look like with a thick hydrogen atmosphere (see cover picture). This planet is a good example of why one should not get too obsessed with liquid water and habitability – because hot, close-in planets are easier to detect than Earth-like ones, we have a lot more data to work with. They offer a lot of very challenging puzzles. Most importantly, by evaporating rock, they give us our best chance to know what rocky exoplanets are made of.

PREPARING FOR THE EXOPLANET CENTURY

The study of exoplanets is poised for another great leap forward in the near future, with many advanced observational platforms due to come online. These include the James Webb space telescope, which will offer unprecedented sensitivity and spectral coverage of thermal infrared wavelengths, making it possible to characterise the atmospheres of smaller and cooler planets. There are many target-finding missions (TES, PLATO, CHEOPS) which will identify nearby transiting planets suitable for follow-up with Webb or with advanced ground-based instruments such as the European Extremely Large Telescope. The UK is well-positioned to take a leadership role in the dawning era of exoplanet exploration, with many UK universities having a strong presence in the field. Oxford is already a jewel in the crown of such efforts, but excellent as it is, exoplanets at Oxford needs to grow in order to take full advantage of the coming new opportunities. We need new initiatives to knit together efforts in Astrophysics, high temperature/pressure physics, Atmospheric Oceanic and Planetary Physics and Earth Sciences. We need new ways of preparing undergraduates and postgraduates for the exciting cross-disciplinary challenges ahead. And we need additional faculty to build the programme. This will be a challenge in a post-Brexit Oxford. Exoplanet research relies heavily on recruiting the best talent worldwide, and in fact many of our star researchers and students come from continental Europe. Further, innovative work on exoplanets relies heavily on funding by the European Research Council.

If Britain is not to be left in the dust, it is essential that the flow of talent to our shores be maintained, and that access to European Research Council funding be maintained, or replaced by equally attractive and flexible UK research council funding. With that, and help from our generous donors, we will be well prepared to continue and expand our leadership role in one of the most amazing scientific revolutions to be visited on humanity in several centuries. ■

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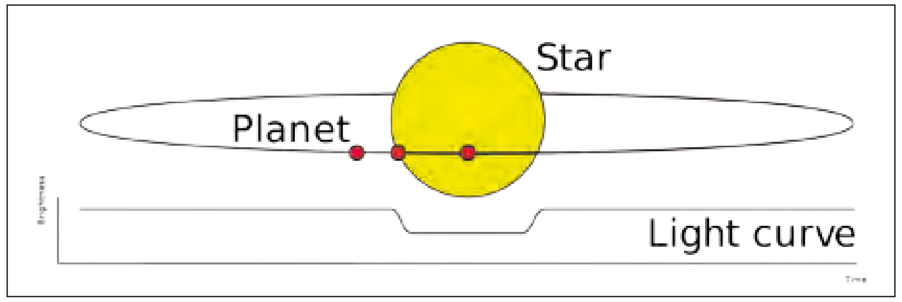
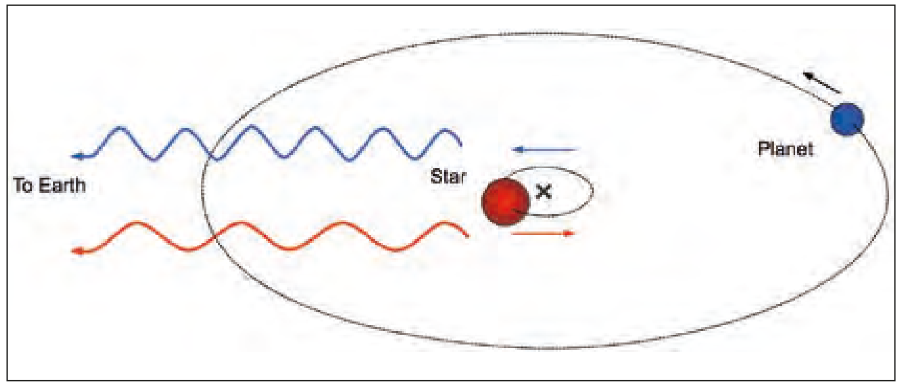
Top figure: Image of a planet transiting a star, for illustration of transit method of discovery of extrasolar planets. Sizes of the star, the planet and its orbit are roughly like HD 209458b.

Bottom figure: Illustration of the radial velocity method for the detection of extrasolar planets.





MAGNETISM ORDERS EXOTIC FERMIONS

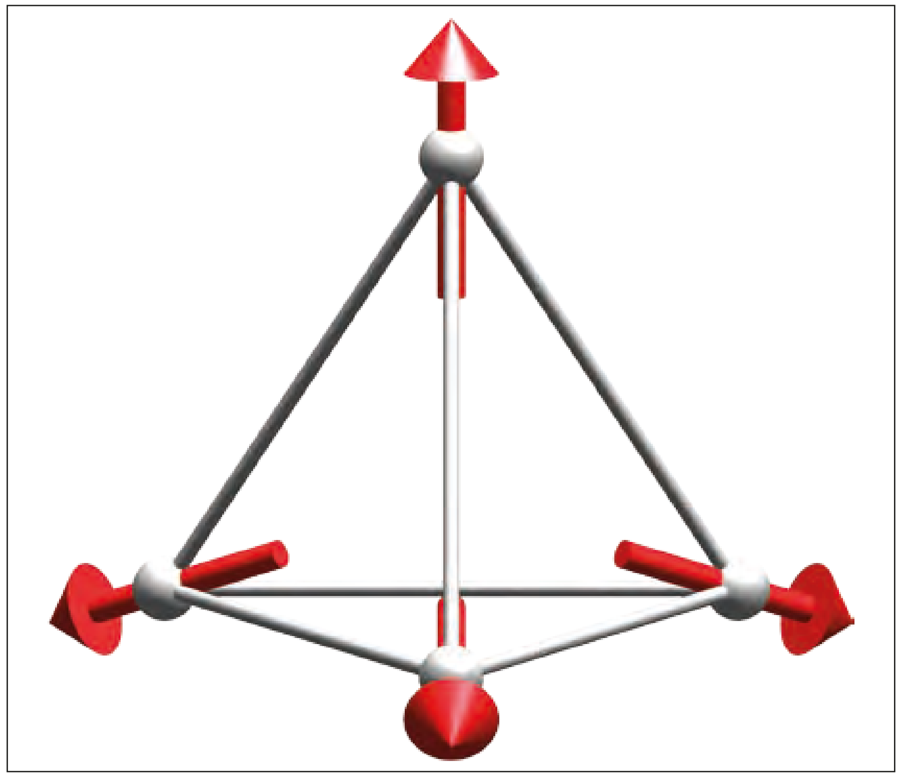
Prof Andrew Boothroyd

An international team led from Oxford and University College London (UCL) has shown that an iridium oxide compound satisfies a necessary requirement for a correlated Weyl semi-metal [C. Donnerer et al., *Phys. Rev. Lett.* **117**, 037201 (2016), and arXiv:1604.06401]. The finding points the way to a possible realization in the solid state of an exotic type of relativistic electron which travels much slower than the speed of light.

Published in 1928, Dirac's famous equation is best known as a complete description of the electron, consistent with both quantum mechanics and special relativity. Less well known are two other types of 'electron' that emerge as solutions to the Dirac equation. One describes a fermion without mass, and the other a fermion with mass but without an antiparticle. These solutions were found by Hermann Weyl in 1929 and Ettore Majorana in 1937, respectively (Majorana disappeared shortly afterwards in mysterious circumstances). For a long time, neutrinos were thought to be Weyl fermions, but the discovery of neutrino masses rules this out. Neutrinos could instead be Majorana fermions, and this remains an open question in neutrino physics.

Incredibly, both Weyl and Majorana fermions have now been found, not in particle physics but in the realm of condensed matter. Bulk materials such as metals, semiconductors and insulators contain unimaginably large numbers of electrons in close proximity. When they are allowed to interact with their surroundings and with one another, electrons, like people, can behave in strange and interesting ways, even masquerading as other types of fundamental particle. Such emergent low-energy electronic excitations are known as quasiparticles.

Orientation of the magnetic moments (shown by arrows) on one tetrahedron of iridium atoms in $Sm_2Ir_2O_7$. The tetrahedra are joined together at the corners to form a network, and the magnetic moments point either all-in or all-out of the tetrahedra.



WEYL FERMIONS IN THE SOLID STATE

Recently, it became clear that Weyl fermions can emerge as quasiparticles in certain crystalline materials called Weyl semimetals. Theoreticians predicted that Weyl semimetals can occur in two types of crystal, one having broken spatial inversion symmetry, and the other broken time-reversal symmetry. Examples of the former type were found in 2015, the first being the compound tantalum arsenide (TaAs), but up to now there have been no confirmed realizations of the latter type.

In the new work, the Oxford–UCL team used a combination of resonant elastic and inelastic X-ray scattering to investigate the magnetic behaviour of single crystals of the cubic pyrochlore oxide samarium iridate ($Sm_2Ir_2O_7$). The results showed that $Sm_2Ir_2O_7$ transforms at a temperature of 110K into a magnetically ordered state in which the magnetic moments on the iridium (Ir) atoms form a network of corner-shared tetrahedra and point either all-in or all-out of the tetrahedra (see figure). Such a magnetic structure breaks time-reversal symmetry but preserves spatial inversion symmetry, as required for a Weyl semi-metal.

TOPOLOGY AFFORDS PROTECTION

The results support a theoretical prediction that pyrochlore iridates could host Weyl fermions, although electronic correlations also revealed by the study could forestall the Weyl semi-metal state in practice. If that were the case, then it might be necessary to tune the electronic structure by chemical modifications or external pressure to form the Weyl semi-metal.

The idea that electrons in condensed matter can behave relativistically but with speeds much less than the speed of light is not new. The conduction electrons in graphene (the two-dimensional form of carbon made of a single sheet of graphite) behave this way, which is the reason why graphene has such extraordinarily high electrical and thermal conductivity. What is special about the Weyl semimetal, however, is that the geometry of the electronic wave functions is topologically non-trivial. As a result, the Weyl fermions are protected against external perturbations such as magnetic fields. Together with their high mobility, this makes Weyl fermions attractive as a route to faster and lower-power electronic and computing devices. ■

THE LHC IN 2016: SOME ANSWERS, MORE QUESTIONS

Many physicists believe that the success of the LHC thus far, including the much-heralded discovery of the Higgs boson, represents but a mere appetiser to the main course. Up to this year the LHC had provided only 0.1% of the total number of planned collisions at the record energy of 13 TeV, and had yet to discover the source of dark matter or the origin of the mass of the Higgs boson itself. This year's collisions offered hope for the next big breakthrough, as tantalising hints of a new particle[1] appeared during the extensive analysis of last year's data collected by the ATLAS and CMS experiments (Figure 1, left[2]). Scientists eagerly awaited the major particle physics conference in August, where results were presented with up to five times the number of collisions as in 2015. While the results showed an unfortunate evaporation of the hinted new particle[3] (Figure 1, right[4]), a clearer picture emerged of the future directions for answering the many remaining questions at the LHC. Oxford physicists have produced many of the important results defining these directions through their work on ATLAS, one of the two experiments collecting data at the LHC. This work includes measurements of the Higgs boson as well as searches for the source of dark matter and for new resonances decaying to muons, quarks, gluons, or Z or Higgs bosons.

1 http://www.nytimes.com/2015/12/16/science/physicists-in-europe-find-tantalizing-hints-of-a-mysterious-new-particle.html

2 http://arxiv.org/abs/1606.03833. *Journal of High Energy Physics* 09 (2016) 001

3 http://www.nytimes.com/2016/08/05/science/cern-large-hadron-collider-particle.html

4 http://cdsweb.cern.ch/record/2206154

BRINGING DARK MATTER TO LIGHT

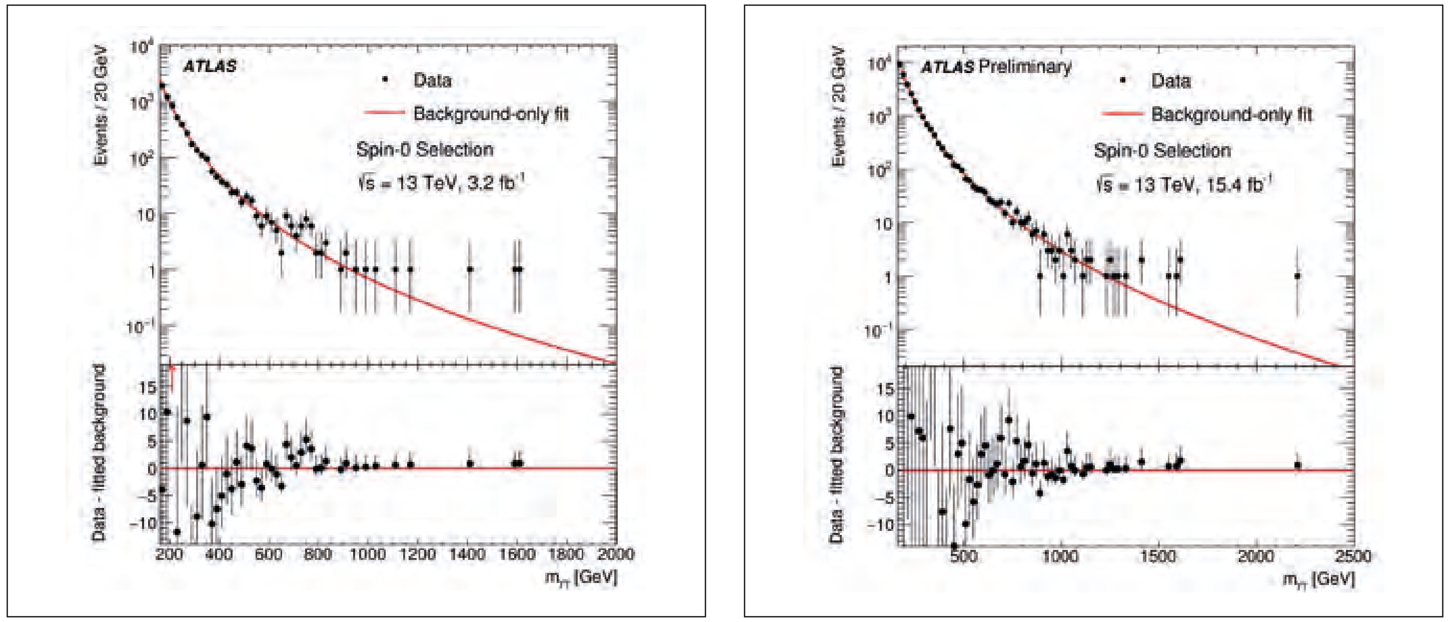
One of the top priorities of the field is the discovery of the particle (or particles) responsible for the large quantity of dark matter in the universe, which corresponds to five times the total mass of the known matter. Naively this particle should have properties allowing it to be produced by the LHC, though both generic and model-specific searches have yet to turn up any signals. The leading model to provide a dark-matter particle is supersymmetry, and this year's results have narrowed the windows for the parameters of this model. A systematic study of viable parameters has been performed by Alan Barr and student Jesse Liu at Oxford[5], which points toward a supersymmetric partner of the Higgs boson as a promising candidate for the source of dark matter. A direct probe of the 2016 data for dark matter produced in association with a Z boson, performed by Oxford's Prof Daniela Bortoletto and Prof Ian Shipsey with postdoc Dr Giacomo Antoni and students Mariyan Petrov and Luigi Vigani, did not turn up a signal[6]. But with the LHC planning to increase the total number of collisions by a factor of ten over the next two years, the first hint of dark matter could be on the horizon.

5 http://www2.physics.ox.ac.uk/news/2016/06/06/supersymmetry-squeezed-at-the-high-energy-frontier, https://arxiv.org/abs/1605.09502, https://arxiv.org/abs/1608.05379

6 http://cds.cern.ch/record/2206138

Dr Chris Hays

Figure 1: The ATLAS analysis of 2015 data (left) showed a hint of a new particle with mass near 750 GeV. The combined analysis of 2015 and 2016 data (right) does not confirm its existence.



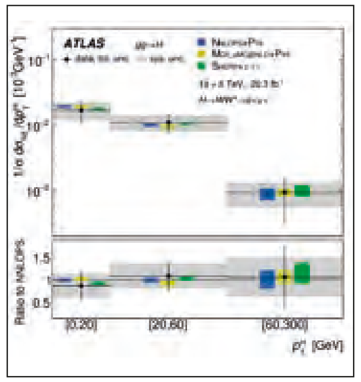


Figure 2: The measured momentum of the Higgs boson transverse to the beam line (points and error bars), compared to three theoretical predictions (blue, yellow, green). The region at highest momentum (60 to 300 GeV) is most sensitive to the presence of new particles beyond the Standard Model.

MYSTERIES AND MEASUREMENTS OF THE HIGGS BOSON

Another top priority is a deeper understanding of the newly discovered Higgs boson. The Higgs mechanism provides mass to all the other particles in the Standard Model through a combination of interactions with these particles and the energy of the Higgs field in the vacuum. However, the source of the vacuum energy is not known, and quantum corrections have an unbounded effect on the Higgs boson mass in particular. Physicists expect the presence of an unknown particle (or particles) to counter these unbounded effects and regulate the mass of the Higgs boson[7]. One possibility is that the new particles are supersymmetric particles, which is a particularly enticing prospect given that one of these particles could also be the source of dark matter.

Detailed studies of the Higgs boson's interactions can give some hints about new particles. With postdoc Kathrin Becker and student David Hall, I have performed a new measurement of the characteristics of Higgs boson production[8] (an example distribution is shown in Figure 2). The coherent combination of a wide range of Higgs boson measurements is an aim I am coordinating within the LHC Higgs working group, and in the process defining new approaches to incisively test for new particles.

Another key step towards understanding the Higgs field is the direct study of the Higgs boson self-interactions. In the Standard Model these interactions are governed by the potential energy of the Higgs field, and they determine the vacuum energy that provides mass to the known particles. The self-interactions affect the pair-production of Higgs bosons (see Figure 3), which is a rapidly expanding effort within the ATLAS and CMS experiments. Oxford's Prof Cigdem Issever, postdoc Dr James Frost, and student Nurfikri Norjoharuddeen are leading two of the most promising analyses[9] within ATLAS to probe these interactions, with studies by Issever, Bortoletto and collaborators suggesting that pair-production will be measurable with the complete LHC data set[10]. This prospect is exciting for many reasons, but most importantly because it opens up yet another avenue to probe for new particles and interactions.

7 http://www.symmetrymagazine.org/article/april-2013/naturalness

8 http://arxiv.org/abs/1604.02997. *Journal of High Energy Physics* 08 (2016) 104

9 http://arxiv.org/abs/1606.04782. *Physical Review* D 93, 052002 (2016)

10 https://arxiv.org/abs/1512.08928. *European Physical Journal C* (2016) 76: 386

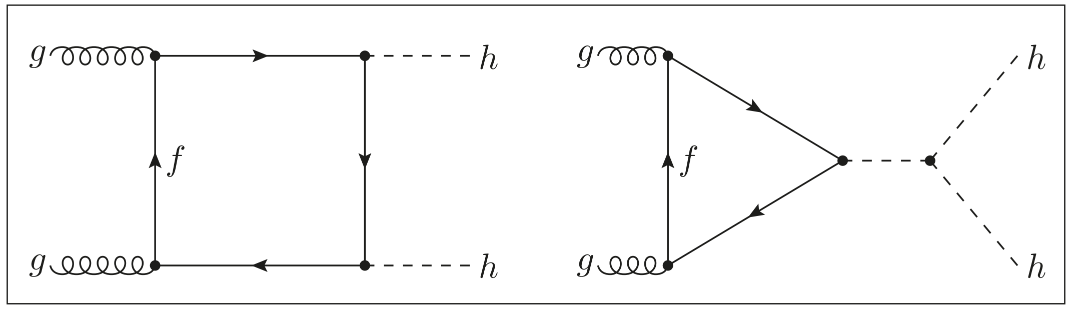
A HUNDREDFOLD INCREASE IN TOTAL COLLISIONS

The study of Higgs boson self-interactions motivates a substantial increase in the number of collisions, which will also expand the opportunities for dark matter discovery. The LHC is scheduled to be upgraded to operate at much higher luminosity (and therefore collision rate) after 2023. This High Luminosity LHC (HL-LHC) will provide this increase by using several novel techniques, including stronger beam focussing using magnets based on superconducting Ni_3Sn (as opposed to the NiTi used in the existing LHC magnets).

The HL-LHC presents many challenges for the ATLAS and CMS detectors. The challenges are particularly acute for the tracking detectors surrounding the beam pipe. The rates will be too high for the existing wire chamber in ATLAS, and the existing silicon detectors will be too severely damaged by the radiation to operate efficiently. The Oxford ATLAS group is a leader in developing a new all-silicon tracker to replace the existing tracker. As well as coping with the radiation damage, the new tracker will need sensor elements with higher granularity to maintain an acceptable occupancy in a given element. The higher luminosity will also lead to much higher data-taking rates, so the data readout will be very demanding.

The new tracker will be based on silicon 'pixel' detectors at small radius with respect to the beam line and silicon 'strip' detectors at larger radius. The Oxford group has many responsibilities on both detector types. For the pixel detectors, we are using new facilities to assemble modules combining sensors with readout electronics. For the strip detectors, the group has many responsibilities, including: the design of a light but stable support structure as well as electrical, optical and cooling systems; validating the reliability of the on-detector components; and finally the development of novel radiation-hard silicon sensors based on CMOS electronics, which allows the functions of the sensor and readout electronics to be integrated into one chip. This wide range of detector development will ensure a robust detector to handle the large number of total collisions to be produced by the LHC. And these collisions could well lead to the next breakthrough in particle physics. ■

Figure 3: The leading-order diagrams for the production of a pair of Higgs bosons at the LHC [10]. The diagram on the right includes a Higgs boson self-interaction, which is determined by the potential energy of the Higgs field.



NOTES FROM THE HEAD OF PHYSICS

Prof John Wheater, Head of Department

Sometimes science grabs the news headlines, for example with the discovery of gravitational waves which we covered in the last newsletter. However, that is relatively rare, and negative results are often just as important. Run 2 of the Large Hadron Collider at CERN has continued through this calendar year and the summer brought the usual crop of conferences with updates being reported by all the experiments – in two of which, ATLAS and LHCb, we play a significant role. Both ATLAS and CMS had found in the 2015 data some hints of a new particle with mass of about 750 GeV (roughly six times the mass of the Higgs Boson). When reported last Christmas this caused a flurry of excitement in the community: could this be the first sign of physics beyond the Standard Model? Unfortunately, as Chris Hays discusses in his article, the much bigger data set we now have shows that it does not exist – the measured particle excesses were just a statistical fluctuation. Intriguingly, no sign of any other new particle has yet shown up and many extended models based on supersymmetry are now being ruled out. There is increasing tension between the ideas and (somewhat technical) preferences of theorists and what the experiments are showing. We may be entering into an intriguing period.

BREXIT

The biggest headline over the summer has been Brexit. What effect will this have on Physics at Oxford? It is hard to say in the absence of any well-defined government policy but it is straightforward to see the extent to which we are exposed. EU funding accounts for about 20% of our research activity, and whether equivalent funding will be available post-Brexit is obscure. Science is a global business and involvement in international projects is dependent on one's scientific reputation and on confidence in one's reliability as a partner; the latter has inevitably taken a blow as a consequence of the Brexit vote. About 25% of the faculty and post-doctoral research staff in the department are EU citizens; it is crucial that they are able to continue living and working here without major upheavals in their status. Again, about 25% of our graduate students are EU citizens; if they become subject to new immigration rules, or their fees become ineligible for UK Government funding, then the numbers will surely decline and with them our broader influence on the continent.

BEECROFT BUILDING UPDATE

On 26 June a gathering of donors, Physics Department staff, and the Beecroft Building project team was held in a 16m deep hole where the Clarendon Laboratory car park used to be. We were there to mark the reaching of the, literally, lowest point in the construction; it was quite a weird experience looking up at the old Clarendon Laboratory from down there. The programme continues to run well and by the time most of you read this we expect the works to be almost back to ground level, with the roof going on in February 2017. The speed is accounted for by the fact that much of the structure is fabricated off-site in a factory, brought in on trucks, and assembled using the tower crane to manoeuvre the components into position. The complexities of constructing a major science building are simply fascinating and I cannot help feeling that it is somehow the fulfilment of an early childhood spent with Lego and Meccano. On another recent site visit we were shown round by a concrete construction specialist; I will never look at a building and think it is 'just concrete' again!

If all goes according to plan, and so far it has, the Beecroft Building will be ready for occupation in December 2017. I am often asked what will happen to the existing buildings. Large as it is, the Beecroft Building only represents about 25% of the space currently occupied by the Physics Department.

The lowest point in the building process.

The above-ground floors have been designed to accommodate the theorists who will move from their current Victorian housing in the Keble Road terrace; that space will be relinquished by Physics and the University will refurbish it and use it for another department, as yet undetermined. The new state-of-the-art laboratories will serve two initial purposes. Firstly, existing activities in totally unsuitable accommodation in the old Clarendon laboratory will move into them; this includes quantum information research and atomic force microscopy which both require much more stable conditions than they currently have. Secondly, we can now embark on new activities that hitherto would have been impossible. Over the next few years we will be recruiting a number of new academic staff and the new facilities that we can provide them with will be an important element in attracting world-leading scientists.

ACADEMIC RECRUITMENT

While writing the previous paragraph I realised that I have never talked about academic recruitment in my piece for the newsletter. Partly, this is because there has been a bit of a lull caused by the UK Government's funding processes, which happens to have overlapped with the creation of the newsletter. However, we are now moving into a period of, I hope, regular recruitments. Over the coming year we will be filling posts in experimental Quantum Information, theory of Quantum Condensed Matter, and Physical Climate Science. The world-class facilities that we can offer in the Beecroft Building will be an important element in attracting world-leading scientists to work in Oxford.

As leading scientists have to start somewhere, I make no apology for ending by returning to the topic of funding graduate students. We are embarking on the first active phase of our campaign to establish the Oxford Physics Endowment for Graduate students, OXPEG for short, which is planned ultimately to support 25 graduate scholarships for outstanding young physicists from around the world. The target of the first phase, which will run to mid-2017, is to raise £3.5m – enough to support five scholarships at any one time. We have made a good start with about £700k pledged at the time of writing. As Martin Lueck, who chairs the Physics Development Board, says in his article there is surely no better way to ensure a bright future for the department. ■

OXFORD PHYSICS

Martin Lueck, Christ Church 1980, is Research Director and co-founder of Aspect Capital, and Chair of the Physics Development Board

... AND FROM THE CHAIR OF THE PHYSICS DEVELOPMENT BOARD

I graduated in 1983 with a BA (Hons) in Physics and came back five years later to collect my MA (Hons) – much to the incredulity of my Canadian girlfriend (and now wife). It still riles her.

It was only much later that I realized what an extremely fortunate period it had been to be at Oxford. Apart from the bonus degree, Her Majesty's Government was generous enough to pay for my entire tuition and housing; investigators at CERN were observing evidence of $W^{\pm}$ and Z^{0} bosons for the first time, and computers were beginning to appear in the practical labs in the Clarendon. Even we undergraduates were at the leading edge of discovery.

LEADING EDGE

I did not stay in academia (to actually *earn* my MA) but went to the City. After a crash-course in finance and a brief stint at Nomura, I joined a fellow Oxford physicist at his father's small commodity broking business where Adam-Sr encouraged us to invest in an early Hewlett Packard workstation and investigate the merits of chart-driven or technical trading. We unwittingly found ourselves pioneers in the new discipline of quantitative or systematic investing and, together with a Cambridge physicist, started AHL in 1987. We felt like the outsiders to the traditional oak-panelled City bastions of polished historians and PPE graduates. Today, physicists are ubiquitous and highly sought after throughout finance.

Oxford physicists are still at the leading edge of discovery in numerous areas including quantum information, neutrinos, photo-voltaics and climate physics. However, it is increasingly expensive and competitive to stay there. Government funding for both undergraduate and graduate students has not kept pace and, in order to compete with the best-funded departments around the world, we must now look to private support.

CULTURE SHOCK

When my wife and I moved our family to the Boston area in 2001 and started looking at schools and thinking about colleges, we had an unexpected culture shock. Not only at the cost of education but that the institutions made it very clear that if you could afford to give back, even just a little, then it was your responsibility to do so for the generations of students to follow. Over time it made eminent sense but this was not a sentiment I had experienced in the UK.

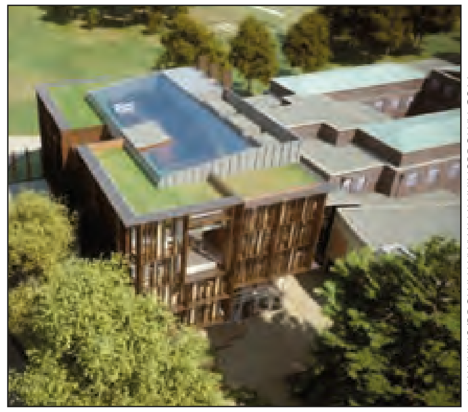
So when I met John Wheater and learned of his plans to expand the department into a new building with state-of-the-art facilities, I very much wanted to help. Through generous donations from alumni and friends of the department we have been able to realize John's vision and the Beecroft Building will be completed next year and occupied early in 2018. It has been extremely exciting to meet some of the faculty and graduate students who will use the new building, where the laboratories, facilities and collaboration spaces will encourage innovation. There is a palpable sense of 'stretch' thinking to try and envisage the experiments that might follow far into the future.

But the Beecroft Building is not a one-off project that guarantees the department's bright future. It is part of a continuous programme of ongoing evolution and improvement. We must now equip the labs with instrumentation; in due course we need to retrofit the dated 1940s labs in the Lindemann Building and, most importantly, we need to ensure that the labs are populated with the best and brightest students to contribute to current projects and to ask the questions that will inspire the work of the future.

BRIGHT FUTURE

The Physics Development Board has brought together alumni from a wide range of eras and careers. I think we are all grateful for the formative experience and solid grounding of a physics education, irrespective of how much we use it now day to day. We are all fascinated to spend time with John and his colleagues to gain an insight into their current and future work, and we are committed to helping support the further development of the department and promoting a sense of shared responsibility to contribute to it.

I am delighted that John recently asked me to Chair the Board and to help the department grow an endowment that will allow Oxford Physics to compete for the very best graduate students. Surely this is the best way to ensure the department's bright future. Please contact me (martin.lueck@aspectcapital.com), John (john.wheater@physics.ox.ac.uk) or Will Thomas (william.thomas@devoff.ox.ac.uk) to find out more about OXPEG, the Oxford Physics Endowment for Graduate students. ■



Left: Prof John Wheater and Martin Lueck at the Beecroft building bottoming up event.

Above: Artist's impression of the finished building.

SQUARE KILOMETRE ARRAY (SKA) PROJECT AND INDUSTRY COLLABORATION

WORLD'S LARGEST RADIO TELESCOPE

The SKA project is an international effort to build the world's largest radio telescope, with eventually over a square kilometre (one million square metres) of collecting area. The scale of the SKA represents a huge leap forward in both engineering and research and development. Detailed design studies and preparation for building and delivering this unique instrument are now well under way. As one of the largest endeavours in scientific history, the SKA will draw on some of the world's finest scientists and policy-makers to bring the project to fruition.

The SKA will eventually use thousands of dishes and up to a million antennas that will enable astronomers to monitor the sky in unprecedented detail and survey the entire sky much faster than any system currently in existence. Its unique configuration will give the SKA unrivalled scope in observations, largely exceeding the image resolution quality of the Hubble Space Telescope. It will also have the ability to image huge areas of sky in parallel, a feat which no survey telescope has ever achieved on this scale with this level of sensitivity. With a range of other large telescopes in the optical and infra-red being built and launched into space over the coming decades, the SKA will perfectly augment, complement and lead the way in scientific discovery.

UK INDUSTRY COLLABORATION

On 27 April 2016 the STFC, UK Trade and Investment, the Knowledge Transfer Network (part of Innovate UK) and the Universities of Oxford, Cambridge and Manchester came together to hold an event at London's BIS Conference Centre to provide an opportunity for UK Industry to hear from the SKA Organisation and from the academics leading the UK design effort. Attendees benefited from networking sessions and held discussions with experts about what will be required to build the SKA; from antenna design, software development and hardware build to cryogenics and data transport. More than 150 people from UK industry attended, along with 40 people from universities and government. The event was opened by Jo Johnson, MP and Minister of State for Universities and Science, who described how the SKA, which the UK is contributing £100m towards, had captured the imagination of people all around the world. The morning featured talks describing the aims, challenges and requirements for the SKA and this was followed by posters, specialised talks and networking in the afternoon.

OXFORD DESIGNS

The telescope will consist of three arrays of antennas: SKA-Mid, consisting of 250 dish antennas, in South Africa; SKA-Survey, a smaller dish array in Australia; and the Low-Frequency Aperture Array (LFAA), also in Australia. Oxford Physics and Oxford's e-Research Centre are involved in three of the consortia which are developing the detailed design of the SKA. The LFAA is one of the major elements of the SKA, comprising an array of 250,000 antennas working at frequencies up to 350 MHz (similar to FM radio). Oxford is leading the design of the hardware that will process the signals from these antennas and combine them into many hundreds of 'virtual dishes', which can be pointed and steered electronically.

In the Central Signal Processing consortium, we are designing the electronics that will combine the signals from these virtual dishes to form images, and also working on the systems that will search the data from the LFAA and the dish arrays for transient and repeating signals, such as those from pulsars. In the Science Data Processor consortium we are developing software systems that will process the huge amounts of data coming out of the SKA, automatically producing science data products that astronomers can use, and storing and disseminating these data around the world. Much of the work, particularly in the hardware design, is being done in collaboration with UK companies who will also benefit from this research as they help us to develop state-of-the-art signal processing systems, which can have applications in many fields outside of radio astronomy. ■

Oxford Physics were represented by our academics Prof Mike Jones, Prof Angela Taylor, Dr Kris Zarb-Adami, Dr Aris Karastergiou and the Department's Senior Knowledge Exchange Facilitator, Dr Phillip Tait and Senior Research Facilitator, Dr Hannah Lingard.

- Organisations from ten countries are currently members of the SKA Organisation – Australia, Canada, China, India, Italy, New Zealand, South Africa, Sweden, the Netherlands and the United Kingdom.
- This global organisation is managed by the not-for-profit SKA Organisation, who have their headquarters at the Jodrell Bank Observatory, near Manchester.
- Whilst 10 member countries are the cornerstone of the SKA, around 100 organisations across about 20 countries are participating in the design and development of the SKA.
- The SKA will require supercomputers faster than any in existence in 2015, and network technology that will generate more data traffic than the entire Internet.

SKA dishes by night. Dr Jamie Leech was among the Oxford physics academics involved.

SKA ORGANISATION/TDP/DRAO/SWINBURNE ASTRONOMY PRODUCTIONS

IOP NAMES OXFORD PHYSICS DEPARTMENT A GENDER EQUALITY CHAMPION

The Department of Physics at the University of Oxford has been named a champion of gender equality in the IOP's Project Juno initiative.

Project Juno aims to address the long-standing issue of women being under-represented in physics at UK and Irish universities, by recognising and rewarding action to address the issue and embed better working practices for all.

The department joins 15 others that have attained Champion status, the highest level awarded within Project Juno, having progressed from being a Juno Supporter and then a Juno Practitioner.

To become a Juno Champion, a department, institute or group must demonstrate that it has embedded the five principles of Project Juno. These concern appointment and selection, career promotion and progression, departmental culture, work allocation and flexible working practices. There must also be a framework in place to deliver equality of opportunity and reward.

Jennifer Dyer, head of diversity at the IOP, said she was pleased to have a new addition to the list of Juno Champions. She said: 'The Institute is delighted that Oxford University has achieved Juno Champion status. The Oxford physics team have worked hard to embed gender equality into their physics environment and we congratulate all those involved in this achievement. Project Juno continues to deliver real results, demonstrating the efforts that physics departments are taking to ensure that everyone has the opportunity to succeed.'

Prof John Wheater, Head of Department, said: 'We are delighted to have been awarded Juno Champion status. We are determined to continue to build on the Juno principles and provide an environment of uniform opportunity for people to succeed as physicists.' ■

SOURCE: HTTP://WWW.IOP.ORG/NEWS/16/JUL/PAGE_67701.HTML

Top: The Oxford *Women in Physics* Group holds regular meetings.
Bottom: Female professors take active roles in outreach and alumni events.

BEECROFT BUILDING BOTTOMS OUT

On 27 June 2016 a 'bottoming out' ceremony was hosted by our construction team Laing O'Rourke. It celebrated reaching the deepest point of the building's excavation 17 metres below ground. The building will house state-of-the-art research facilities and become the new home for our theoretical physics, condensed matter physics and quantum physics groups. Three of the building's seven floors will be below ground.

The ceremony was attended by approximately 50 people, including academics, major benefactors, and members of the construction and architect teams. Prof John Wheater thanked those who had contributed their time, expertise and money to the project and spoke about the future of the building. Key benefactors participated in finishing the concreting of the base – this involved shovelling concrete from a wheelbarrow into a specific area that was left unfinished for this purpose, and then trowelling it smooth. ■

OXFORD OUTREACH

Prof Chris Lintott

Oxford Physics' outreach programme is becoming more international thanks to the efforts of astrophysics DPhil student Sandor Kruk. Sandor, who works with the Galaxy Zoo team to study the effect of bars on spiral galaxies, has led the development of two projects which connect school students across the world.

The first, which builds on the Department's existing support for the nationally-organised Physics Olympiad, saw the first UK entry in the Astronomy and Astrophysics Olympiad. The competition involves a challenging mix of physics problems and observational astronomy; in its first year, more than forty schools entered students. The best of them made up the team who came second in the international competition held in Magelang, Indonesia – a remarkable result for a programme in its first year.

Sandor was also involved in the first Oxford for Romania summer school, held in September this year. Thanks to the efforts of young scientists in Oxford's Romanian community, 21 students from a diverse range of backgrounds spent a week at the University, learning amongst much else quantum optics, exobiology and even salsa dancing.

Both activities help connect the Department to new schools and audiences, and we're happy to help Sandor with his quest to tell everyone about Oxford Physics. ■

Below left: Oxford for Romania summer school students

Below right: Charles Barclay (far left) and Sandor Kruk (far right) with the UK Astronomy and Astrophysics Olympiad team in Magelang, Indonesia

YEAR 12 SUMMER SCHOOL

Twenty students from across the UK took part in the first Oxford Physics Year 12 Summer School at the end of July. The week aimed to give students a flavour of what it's like to study in a physics department.

The students worked in pairs on a research, outreach or laboratory project. At the end of the week they presented a poster of their work to their peers. They also took part in a central programme of activities that involved physics talks, laboratory tours, careers sessions and a problem solving workshop. Students' project topics included exoplanets, quantum computers, muons detection and radio astronomy.

Work experience helps students gain insight into the working environment and to develop an appreciation of the real life applicability and relevance of what is learnt at school. ■

'I learnt how to use the germanium and the Timepix chip detectors. I also learnt how to use various pieces of software to plot and analyse results obtained from the detectors.'

'I particularly enjoyed the department tours and meeting the ATLAS research group. I learnt about the LHC and how the machines make the detector components, which was so interesting.'

— Summer School participants

Students enjoyed a whole week of activities and a chance to find out first hand what it is like to work in our department

Students presented their experiment or topic to the group

Students had a chance to learn and share experiences gained during their week

FESTIVAL TIME FOR OXFORD PHYSICS

Oxford Physics events featured throughout the new-look Oxfordshire Science Festival programme, allowing us to engage with more than 800 people at the end of June. However, despite a pleasant summer overall, we weren't lucky with the weather!

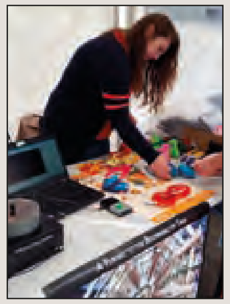
Researchers and undergraduates had to brave heavy rain on Broad Street for **Space Day**, attracting passers-by with a series of space-themed activities. Dr Cat Hayer, who made comets out of dry ice during the event, reported 'we were all completely soaked through in almost a minute, but during the breaks in the clouds there were a lot of happy faces and nice people chatting to us.'

We also ran two stalls at the **Oxfordshire Science Fair** over the opening weekend. Dr Sam Henry led a particle physics stall on Broad Street, during thunder and lightning and a freak gust of wind that almost blew away the gazebo. But despite the weather causing a few complications, Sam commented 'we had a fun weekend running the stall. It was great to talk to everyone who stopped by. Many had heard about CERN and the Large Hadron Collider, and were excited to learn about what it was like to work on these projects.' The stall included a cloud chamber, CERN@school detector, Build Your Own Universe Lego kit, and Particle Zoo toys.

The **NQIT (Networked Quantum Information Technologies) team**, who had also recently participated in the Cheltenham Festival of Science, engaged visitors in the shelter of Oxford Town Hall. They explained how to build a quantum computer through hands-on demonstrations of the physics involved, and introduced the key potential applications of this exciting technology using specially-designed games.

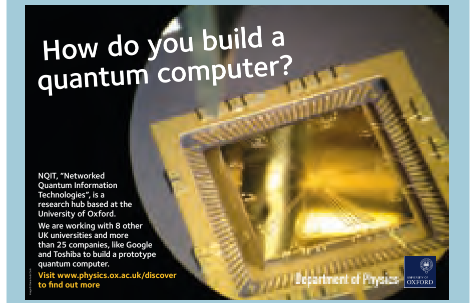
Researchers across Biophysics ran their first **research showcase event** entitled 'Physics of Life' in the Department. The event welcomed visitors to immerse themselves in the living nano-world with demonstrations, stalls, talks and lab tours to see experimental equipment in action. The festival programme also included a number of exciting talks by members of the Department including Prof Chris Lintott, Prof Jo Dunkley, Fran Day and Prof Ian Shipsey.

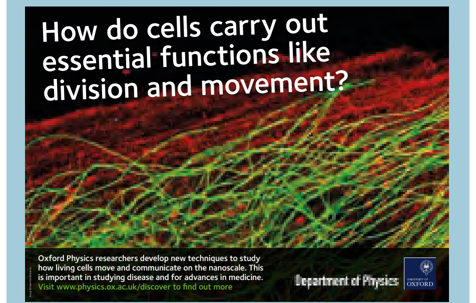
The festival provided a valuable platform for engaging the public with Oxford Physics research. However, the events couldn't have happened without the many volunteers who gave up their free time to participate, some of whom even had to brave the elements to do so. Thank you to everyone who shared their enthusiasm for physics. We look forward to next year and have fingers crossed for sunny skies. ■



Department Posters

We have produced a collection of six posters highlighting some of the work that goes on at the Department. These were produced with the intention of sending to schools or other organisations that may like to display them in their classes. We have a limited number; if you would like a copy, please email Dr Sian Tedaldi at the Outreach Office: sian.tedaldi@physics.ox.ac.uk.





ALUMNI RECEPTION AT CANADA HOUSE, LONDON

Last July we hosted an alumni event at Canada House, Trafalgar Square, London. The event took advantage of a special exhibition showcasing the world-class science of the Sudbury Neutrino Observatory, which was acknowledged by last year's Nobel Prize. The event started with a warm welcome by the Senior Trade Commissioner for Canada House, Mr Mark Richardson. The Head of Physics, Prof John Wheater, and the Head of Particle Physics, Prof Ian Shipsey, then addressed a crowded room overlooking beautiful Trafalgar Square.

Thank you for organising an excellent reception at Canada House yesterday. It looked like a very good turnout of Oxford10 youngsters and Physicists of all ages and it was an impressive display – if a little packed! — Martin Lueck

© STUART BEBB / UNIVERSITY OF OXFORD

All guests had the opportunity to visit the exhibition on neutrinos, with personal guidance from Profs Daniela Bortoletto, Nick Jelley and Steve Biller and students Roxanne Guenette and Tomislav Vladisavljevic. The exhibition was accompanied by drinks and a canapé reception.

For the first time, we invited the younger alumni group *Oxford10* to take part and we were delighted to welcome about 30 of their members to the event. We are very pleased to host the neutrino exhibition in the Physics Department at the time of press, so all are welcome to come and visit. Please give us a call in advance, to make sure it is still here. More details on the opposite page, under 'events'. ■

SATURDAY MORNINGS OF THEORETICAL PHYSICS

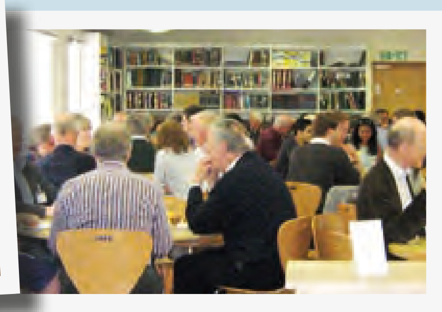
The tenth instalment of the Saturday Mornings of Theoretical Physics took place on 21 May and was devoted to string theory. String theory concerns the dynamics of one-dimensional 'strings' that move in a ten-dimensional space-time. Originally, the theory was proposed in 1968 as a possible model of strong interactions and it has since provided a wide range of applications to mathematics, particle physics and quantum field theory. The aim of the event was to provide an overview of the field and give an introduction to some current research directions, or in short to answer the question 'What is string theory, and why are theoretical physicists willing to devote their lives to it?'

Prof. Joseph Conlon ('String Theory: Then and Now') opened the event by giving a historical overview over how string theory evolved since its birth in 1968, via the *First Superstring Revolution*, *The Age of Excitement*, the *Second Superstring Revolution* to its present status. He outlined the key ideas and discussed how they have matured over time.

A key aim of string theory is to unify quantum theory and general relativity. In order to achieve this it must recover the Standard Model of particle physics in the appropriate limit.

Prof Andre Lukas ('String Theory and Particle Physics') discussed efforts aimed at recovering known particle physics as a limit of superstring theory. This requires 'folding up' six of the ten dimensions to a microscopic size. The various observed particles are then obtained as different oscillatory modes of the string.

Finally, Prof. Andrei Starinets ('String Theory, Holography and Quark-Gluon Plasma') explained how methods originating from string theory can be used to answer difficult questions in quantum field theory, by mapping them into 'dual' problems in classical gravity. In particular, this allows one to understand properties of the quark-gluon plasma formed in heavy ion collisions at modern accelerators such as the LHC.



The talks were followed by very lively question sessions. As usual there was plenty of time for catching up with old friends during the breaks, and for discussing physics with members of the Rudolf Peierls Centre for Theoretical Physics. ■

The next event is scheduled for 29 October 2016 and will focus on 'More is different – how states of matter emerge from quantum theory.' The first event in 2017 will take place on 18 February. See website for details.

DEPARTMENT NEWS & EVENTS

INDUSTRY COLLABORATIONS

The Department of Physics works with companies to share expertise, develop new ideas, provide services and commercialise research. We welcome working with new business partners. We engage with industry in many ways, through research collaboration, contract research, consultancy and student projects. We are experienced at sourcing collaborative funding and can provide support to develop new project proposals.

Discover how the unique expertise at the Oxford Physics Department can help. Contact Dr Phillip Tait, Tel +44 (0) 1865 283006, Email Phillip.tait@physics.ox.ac.uk, or visit www.physics.ox.ac.uk/enterprise

PHYSICS PICNIC & BBQ

At the beginning of summer we hosted a picnic and BBQ for all staff, students and alumni. This informal and fun event was attended by more than 150 people. We thank the lovely team at the University Parks for allowing us to host what we hope will become an annual event.

CHERWELL-SIMON MEMORIAL LECTURE

On 13 May Prof Lisa Randall (Harvard) delivered the 56th lecture in this series on 'Dark matter and the dinosaurs: the astounding interconnectedness of the universe'. The lecture explored a speculative hypothesis in which the comet that may have triggered the mass extinction of the dinosaurs was dislodged from the Oort cloud at the edge of our solar system by a disk of dark matter. Pictured from left: Prof John Wheater, Monica Mendelssohn (daughter of Prof Kurt Mendelssohn), Prof Ian Shipsey, Kathrin Baxandall (daughter of Prof Francis Simon) and Prof Lisa Randall.

FROM OXFORD TO MARS!

On 19 October, if all has gone well, the European Space Agency will have achieved its first successful Mars landing. The Schiaparelli lander carries a wind sensor built in Oxford's Physics and Engineering Science departments. Follow the mission at exploration.esa.int.

CAREERS SERVICE

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

STUDENT ACHIEVEMENTS

CHRIS BALANCE and **MIREIA CRISPIN ORTUZA** were awarded Springer Thesis Awards for the 'best of the best' series, in which internationally top-ranked research institutes select their best thesis annually for publication. Nominated and endorsed by two recognised specialists, each thesis is chosen for its scientific excellence and impact on research. Balance's thesis was entitled 'High-Fidelity Quantum Logic in Ca^+'. Ortuza's thesis was entitled 'High Jet Multiplicity Physics at the LHC'.

MAREIN RAHN has been awarded the Nicholas Kurti Prize 2016 for distinguished work by a third year graduate student in Condensed Matter Physics.

DAVID MCMEEKIN, has been awarded the David Ryan Prize 2016 for the best research presentation by a second year student at the annual poster session.

SUZIE SHEEHY was awarded the IoP HEPP Group Prize Science in Society for outstanding public engagement in accelerator science and particle physics.

FORTHCOMING ALUMNI EVENTS

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

'NEW EYES ON THE UNIVERSE' EXHIBIT

Don't miss this amazing exhibition at the Denys Wilkinson Building, open from **22 September 2016, 9:30am–4:30pm daily.** Created by SNOLab and Science North (Canada), the exhibition highlights the achievements of Prof Art MacDonald and his team (including some Oxford Physicists) through their work on neutrinos, which resulted in a Nobel Prize. All welcome, including general public. For private visits, groups or special events please contact the alumni office to make an appointment.

SATURDAY MORNINGS OF THEORETICAL PHYSICS

29 October 2016 Denys Wilkinson Building, Oxford. 'More is different – how states of matter emerge from quantum theory'. The next Morning of Theoretical Physics event will take place on 18 February 2017.

AOPP EVENT AT THE ROYAL SOCIETY

11 November 2016 Following last year's success, the Atmospheric, Oceanic and Planetary Physics group, led by Prof David Marshall, will host another evening at the Royal Society on the theme of space instrumentation and exploration, followed by a drinks and canapés reception.

PARTICLE PHYSICS CHRISTMAS LECTURE

3 December 2016, 11am–4pm, Martin Wood Complex, Oxford The lecture, entitled 'The future of particle physics', will be given by Prof John Womersley (STFC). The event will be hosted by Prof John Wheater and Prof Ian Shipsey and will include buffet lunch and afternoon drinks.

CHRISTMAS CAROLS

19 December 2016, University Church of St Mary the Virgin, Oxford Hosted by Jim Williamson, with the participation of many members of staff in the choir, and followed by drinks and mince pies.

PHYSICS LECTURE AND RECEPTION

11 March 2017, Oxford & Cambridge Club, London Further details to follow.

All these events are free, but we have limited capacity so tickets will go on a first come, first served basis. To avoid disappointment, visit our website regularly for updates.

LETTERS TO THE EDITOR

Letters are welcome and should be addressed to ***newsletter@physics.ox.ac.uk***

Memoires from Australia

Many thanks for the Department of Physics newsletter which I always enjoy reading. One thing that interests me is how much the Physics Department has changed in its relations with the undergraduates. In 1957 when I matriculated it was inconceivable there would be a leavers' reception and a group photo. Life was focussed on the College and the only group photo I participated in was of our college matriculants. The Physics Department was the venue for lectures and practicals and that was that.

We gained the impression that attendance at lectures was optional, so it had to be an especially good lecturer or topic to attract us. We would sometimes attend the first lecture to suss it out. The lecturer would start by recommending text books on the lecture topic; we decided the one book he did NOT include was the one he lectured from. I wryly remember one lecture series in which my friend, Mike Dale, and I were interested. It was on 'Noise', as in signal-to-noise and Johnson and shot noise in thermionic valves(!). There were about two dozen of us at the first week's lecture, the next week about half a dozen and the third week only Mike and myself. No lecturer. We were wondering what to do when he poked his head into the theatre, looked surprised and said there had never been any attendees after the second week of his lectures in the past. But if we would like to come back next week, he would prepare a lecture for us. We did and he did. Although I went to few physics lectures, I attended many lectures in other faculties which were given by high profile academics: the philosophers Ayer and Austin, the historians AJP Taylor and Hugh Trevor-Roper, and the lawyer Hart.

Although the Physics Department was indifferent to whether we attended lectures, it was insistent we went to the practicals, which I found most interesting. In my second year, my partner was an American Rhodes scholar who decided he had better things to do than attend physics practicals. So he prevailed on me to answer for him – which I duly did. When the female lab assistant came round to tick off the roll, I explained that my partner was in the toilet or getting some liquid nitrogen u.s.w. and had him ticked off. He would later take my practical note book and a make fair copy of my results and come in the next day long enough to get it checked by one of the DPhil candidates who were employed for that task. Most of these DPhils were very relaxed about their responsibilities and would happily sign off the experiment unless there was a glaring problem. The exception was someone whose name, if I remember correctly was Baggulay, who regarded undergraduates as a lower form of life; his aim was to make things as hard as he could for us. Rather than avoid him, we made a point of choosing him with the intention of challenging him. I now realise that his provocation was a deliberate and commendable educational tool.

Our tutor was Dr Michael Baker. I realise that, in reminiscences of Oxford, it is *de rigour* to praise one's tutor, but in Dr Baker's case it is not hollow praise. My one regret is that I did not make greater use of his knowledge – entirely my fault. Looking back on it, I am not sure that one-on-one tutorials in the sciences have the same benefits as in the arts, because there are basic necessary physics and mathematics that must be covered as opposed to studying and making a presentation on a topic. There was an additional problem: the syllabus was very vague. For example, the thermodynamics syllabus stated something like: 'knowledge of thermodynamics at a level appropriate for an Honours degree'. Not very helpful. We overcame this problem by working through old examination papers and then, at our tutorial, using them as a base from which Dr Baker would expand on what we were expected to know, and where to find it.

In our last year, Mike Dale and I decided to take the Theoretical Physics option, not because we did not find the practicals interesting, but because we realised that we needed a more complete theoretical background to understand what was going on in the forefront of physics. Our tutor was a female DPhil student. She was obviously very capable and sharp as a tack. The only problem was that she had no idea what the syllabus was, and there seemed to be no way to find out, as there were no past papers (the course was introduced that year). Mike and I discussed whether to bring the tutorial problem to the attention of the authorities but we decided not to, out of a sense of loyalty to our tutor. Not surprisingly, when the exam came, I was lost. In the end I handed up my answers after half an hour of frustration.

Our Theoretical tutor was the only female academic on the Physics Department staff that we came across – all the lecturers were male. Of the 140 physics matriculants in our year, we had 4 ladies. They were all very diligent, and we proudly referred to them as 'Our Firsts'. Other than to say a friendly 'hello', we had nothing to do with each other as our social life was entirely focussed on the College.

The bottom line is that from my time at Oxford I gained a lifetime's interest in physics. I am aware of what the acronyms 'LIGO' and 'LHC' mean and that Dr Schmidt of the Australian National University gained a Nobel Prize in Physics for his work on supernovae!

With best wishes
Keith Lloyd, Merton 1957
Adelaide, Australia

Keith Lloyd, Merton 1957
Adelaide, Australia

Oil painting of Prof Terence Meaden in 1992 by Maureen Oliver

Terence Meaden at work in Rooms 107–108, 1958

Prof Terence Meaden's memories of the Clarendon

Dr Mike Wells' article about liquid helium-3 at the Clarendon laboratory reminded me how much it was being utilized 50 years ago when I was there. As a post-doctoral fellow I was in Dr Mendelssohn's group 1961–63, using liquid He-3 to cool highly radioactive metals to 0.4 Kelvin.

My Oxford story began in January 1953 when sitting the physics entrance examination at St Peter's, age 17. Being only in the second-year sixth form at a grammar school in Trowbridge, to everyone's surprise I passed. Later, after physics finals when Dr Mendelssohn was inviting me to join his superconductivity research group, he told me I had just missed a first. I agreed to work on radioactive actinide metals in cooperation with the Plutonium Research Division at AERE, Harwell, led by Dr James Lee. So after Official Secrets Act clearance, I was building cryostats in both places. For Harwell it was the first research done below liquid nitrogen temperatures.

In my doctoral research (1957–61) temperatures were lowered to 0.75 K by pressure reduction in He-4 cryostats. At AERE the cryostat was combined with an argon-filled glove box, while in Oxford the dangerous specimens were sealed in copper capsules ('Electronic properties of thorium, uranium, neptunium and plutonium at low temperatures.' 1963. Proc.Roy.Soc. A276, 553–570).

Thorium was superconducting at 1.4 K and uranium at 0.86 K, so we needed to know whether plutonium and neptunium might be superconductors at temperatures achievable by a He-3 liquefier. We built one (1961–63) in collaboration with the outstanding Clarendon workshop. Our liquefier, using 600 ml of He-3 gas at NTP, was capable of reaching 0.38 K. Experiments were complicated by the high toxicity of these metals with added problems from internal self-heating, so we had to ensure the cryostat could not get contaminated by alpha-radioactivity (Meaden, GT and Shigi, T 1964 'Search for superconductivity in neptunium and plutonium using a new liquid helium-3 cryostat' *Cryogenics 4*, 90–92).

My Clarendon years were unforgettable. As an undergraduate I had regarded Nicholas Kurti (1908–98) and Kurt Mendelssohn (1906–80) highly through lecture attendance. Dr Mendelssohn spoke perfect English, but not Dr Kurti who was born Hungarian and had been a postgraduate student in Berlin under Franz Simon (1893–1956, FRS 1941, knighted 1954). These distinguished scientists were invited by Frederick Lindemann to leave Nazi Germany to create a world-class low-temperature laboratory in Oxford. In Berlin Lindemann (1886–1957) had been a student of Walther Nernst (Nobel prize 1920 for thermochemistry research). He was Winston Churchill's scientific adviser from the 1930s, and was Lord Cherwell when I attended his lectures in 1954. As head of the Clarendon 1919–56 Lindemann also invited Heinrich Kuhn (1904–94, FRS 1954, optical spectroscopy) to leave Germany for Oxford. Upon retirement the new head was Brebis Bleaney (1915–94, FRS 1954), another of Simon's doctoral students.

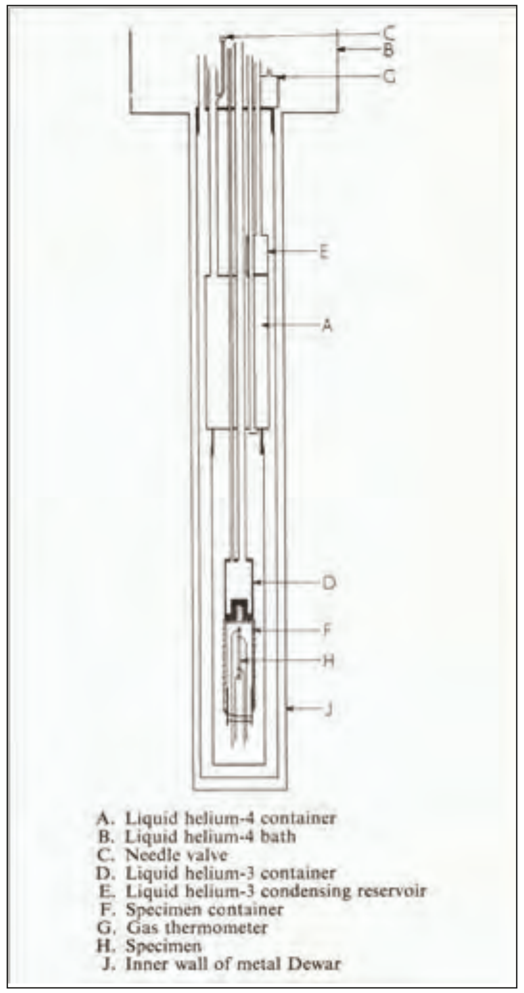
Mendelssohn and Kurti were Fellows of the Royal Society. Mendelssohn – the first to liquefy helium in Britain in 1933 – got his FRS (1951) for studying superfluid liquid helium II. Kurti's spectacular achievement was the adiabatic demagnetization of paramagnetic nuclear spin systems that took cooling to a millionth of a degree Kelvin (FRS 1956). When I arrived at the Clarendon (1957), Martin Wood (b. 1927) – the future founder of Oxford Instruments (FRS 1987, knighted 1986) – was already experimenting with superconducting magnets.

In Oxford my cryostats were in the double room 107–108 and room 112. Between them were Kurt Mendelssohn's office 109 and Ken Mayne's room 111. Harry Rosenberg (1922–93), formerly a student of Mendelssohn, was in Room 106 with John Keyston. As for the thesis and *viva voce* in 1961, my examiners were Dr Arthur Cooke of the Clarendon and Prof BS Chandrasekhar who was in London on sabbatical from Case Western Reserve University, USA.

In every respect these were exciting, memorable years – a joy to have been part of this world-famous department.

Best wishes
Terence Meaden

The helium-3 liquefier for studying radioactive specimens



FIVE MINUTES WITH...DILLON LIU

DPhil student in Theoretical Physics

Tell us a bit about your background

I grew up in a New Jersey suburb of New York City. I studied applied physics at Columbia and spent my summers doing research across the United States, at Louisiana State University, Los Alamos National Lab, and UCLA. Currently, I'm doing a DPhil in quantum condensed matter theory with Prof John Chalker.

When/how did you decide to become a physicist?

I left school a year early to study physics at university, so it was certainly clear by then that I wanted to pursue physics. I've always enjoyed solving problems and have long had an appreciation for using basic principles to explain more complicated phenomena.

Why is it important to study physics?

The usual examples range from modern technology to essential medical tools. An overlooked feature of physics is its simplicity compared with social sciences, humanities and even other natural sciences. Physics has progressed on general principles and repeated hypothesising and experimenting. The astonishing reliability of some of these principles has allowed for the development of invaluable theoretical work.

Can you explain the work you do?

Problems in condensed matter physics often require consideration of many particles and interactions between them. One of the projects I've worked on was about geometrically frustrated magnets. In some magnets, the magnetic moments line up together. In others, the moments anti-align. However, if magnetic moments are located on corners of triangles, then it's impossible for each to anti-align with all of its neighbours. This is the simplest example of a frustrated magnet, and the basis for the model I studied. We used Monte Carlo simulations with hundreds of parallel computing processors and analytical results from field theory to map out the phase diagram of a three-dimensional frustrated magnet and to examine correlations in the system. The simple model can explain quite surprising results from experiments on a real material here at Oxford.

What are the current challenges in this field?

Geometrically frustrated magnets are just one example of condensed matter systems in which degeneracy and strong correlations lead to unexpected phenomena. These sorts of properties arise in disordered and non-equilibrium systems as well. Understanding these will be essential to bridge the gap between simple physical models and the most complicated systems that we come across in real life.

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

While it's exciting to point out examples like quantum computing, nuclear fusion, a better understanding of the mind, I'm most excited about scientific breakthroughs that no one sees coming. For instance, the vast progress and innovation driven by modern computers and mobile devices rests on the development of the transistor. It seems unlikely that John Bardeen and company foresaw us walking around with a few billion transistors in our pockets.

On a slightly different note, I'd like to see a breakthrough of scientific literacy and awareness. Basic scientific knowledge is so helpful for a variety of issues that come up in everyday life. Furthermore, so many people find science fascinating, but feel intimidated or don't know where to start learning about it.

Group photo from Advanced Working Group on Many Body Localisation 2016

How did you end up at Oxford?

Having been in the UK for three years now, it seems funny to think that anyone would overlook Oxford when considering a doctorate in physics. When I think back to my time as an undergraduate, there's no question that more American students should consider Oxford. Although it required a bit more planning and preparation, coming to Oxford for my doctorate meant being in an academic setting and university unlike any in the US. All of the cultural differences and quirks have given me an experience that I am very happy to have had.

Though it's difficult to compare with programmes in other countries, I have been incredibly happy with the culture, especially in the physics department at Oxford. I feel motivated and enthusiastic about coming to work on a daily basis and I get support from faculty, post-docs and other students. My first three years at Oxford were supported by a Marshall Scholarship, for which I am tremendously grateful. I would highly recommend overseas students to consider Oxford for a DPhil in physics.

Can you describe your daily routine at Oxford?

Usually my day starts with water – on top of the water for rowing or sometimes covered in water during the walk to the office. As a theorist, I spend most of my time discussing ideas, programming computer models and simulations, and reading papers. Some of my favorite parts of the day happen in the discussion room of the Rudolf Peierls Centre. The break for tea and the sandwich lunches are fantastic opportunities to talk about non-physics topics (and occasionally physics, too) with students and colleagues from other sub-fields.

What has been most surprising about studying physics at Oxford?

The proximity to so many European countries has given my DPhil a very international feeling. Although I expected this to some degree, I didn't realise how many different opportunities it would translate into in terms of talks, conferences and workshops.

What are your plans for the future?

Hopefully I can continue doing research in condensed matter physics. I expect to continue working on challenging and interesting problems whose solutions help better describe the world around us. ■

ALUMNI STORIES

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

CHRISTOPHER ROBERTS, PEMBROKE 1949

President of the Royal Photographic Society 1982

Photo taken at RAF Scampton in Lincolnshire, the former home of the Dam Buster Squadron, 617, and now the home of the Red Arrows

Cox Pembroke 3rd eight 1951

My introduction to physics coincided with the beginning of the war and my first year at my local grammar school (Queen Mary's Grammar School, Walsall). The war and its aftermath dominated my life for the next ten years or so, involving two years national service in the RAF prior to my arrival at Oxford in 1949.

I was aware that the Clarendon had made significant contributions to the war effort. Lord Cherwell, who was Churchill's scientific advisor, was still active and lectured to us on the Philosophy of Science but it was only later that I learned that Simon and Kurti had perfected a method of separating uranium 235 and 238 isotopes for the atomic bomb project. In addition, Griffiths and Cooke developed a modified klystron oscillator that was used in H2S air radar equipment for Avro Lancaster bombers that I maintained during my service with the RAF.

Simon, Kurti and Mendelssohn had established outstanding research in low temperature physics and all of them gave lectures. I think that it was Kurti who taught most frequently and certainly he was a most entertaining lecturer. He was a keen cook (he coined the term 'molecular gastronomy' for the application of science to cooking) and we did get the occasional tip on the production of good food. I remember that one Michaelmas term he advised us on making mince pies for Christmas, which involved lacing them with brandy using a hypodermic syringe.

COLLEGE LIFE

The majority of the 80 or so physicists in my intake were former national servicemen and there were only 4 women (5%). Today there is about twice the intake with about 20 women (12.5%). Wartime rationing was still in force. Clothing rationing ended in 1948 but food rationing continued until 1954 soon after I went down. Game was exempt from food rationing and this may account for the fact that we ate jugged hare every week in College. All the Colleges were segregated but there was much social interaction between ladies' and men's colleges. Presidents of the Union at the time who became well known were William Rees-Mogg and Jeremy Thorpe. Michael Heseltine came to Pembroke a year or two after me. The college was keen on inter-college sport and I was advised at a Pembroke Collections at the beginning of term to take up sport. As a result I was in the Pembroke tennis, badminton and squash teams and also coxed one of the eights.

A CAREER WITH KODAK

I was the only undergraduate physicist at Pembroke in my year. My moral tutor Doug Brewer (DPhil, later Professor) was the Physics Don at Pembroke, but I had tutorials at other Colleges. He pointed me in the direction of a career in photography, which was my hobby, and after two vacation jobs with Kodak I joined their Research Laboratories at Harrow in 1952. Whilst there I worked in colour photography research and attended a postgraduate course on the physics of colour and vision at Imperial College London. I retired from Kodak in 1993 after 41 years – almost unheard of nowadays.

By today's standards Kodak was very paternalistic and provided an enjoyable environment for its employees. There were many recreational and sports facilities, and with other retirees I am enjoying a generous final salary based pension introduced by Kodak Ltd. I met my wife Ann (née Partridge) there, who also read physics at Oxford at St Anne's College. At that time there were several photographic companies worldwide, each with a research laboratory, and Kodak valued and supported representation on national and international photographic organisations. I joined the Royal Photographic Society and became its President in 1982 and also represented the UK on the International Committee on the Science of Photography, serving as Secretary for several years. There was a need for international conferences on photographic science and I inaugurated through the Royal Photographic Society a series of annual residential conferences on photographic science at Oxford and Cambridge colleges that continued for many years.

After I retired from Kodak I retained my role as company Archivist and as the profitability of Kodak declined I looked for a suitable custodian for both the Archive and also books and journal runs from the Research Library, which had closed. Following discussions with local universities, which were unproductive, the British Library agreed to the transfer of ownership of the Archive from Kodak Ltd and in consequence it is now well looked after at the St Pancras site and is much used by researchers from the UK and from Europe. De Montfort University, Leicester, accepted the books and journals from the Kodak Research Library, thus augmenting their research facility for flourishing degree and postgraduate courses in the history of photography. ■

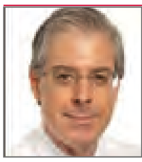
COMINGS, GOINGS & AWARDS...

GOINGS...

In September 2016, **PROF JO DUNKLEY** (sub-department of Astrophysics) moved to the Department of Astrophysical Sciences at Princeton University to begin her new post as a Professor of Astrophysics. Jo, a former postgraduate student at Oxford, is one of the world's leading observational cosmologists and the recipient of many awards for her work. She has played a leading role in both the WMAP and Planck collaborations, two satellites dedicated to observing the Cosmic Microwave Background radiation which have led to cosmological models of unprecedented precision. Such precision now provides compelling evidence for both an inflationary epoch and a Dark Energy component of our universe. While we shall miss Jo's lively presence and the excitement she brought to cosmology research at Oxford, we congratulate her on her new appointment. We look forward to hosting her as a frequent distinguished visitor.

DR MICHAEL TEPER has retired from the Department this Autumn. Mike graduated from the University of Sussex and completed his PhD at the University of London in 1974. His first steps in particle research were in the phenomenology of the strong interaction. Postdocs at DESY in Hamburg, LAPP in Annecy and CERN in the early eighties brought him in contact with QCD, the theory of quarks and gluons. That was a period when a rapid evolution of numerical simulations of a discretized version of the theory known as lattice QCD took place. Mike immediately grasped the importance of this development and brought it to the UK. After various positions there, he was asked by the inventor of the 'naive' quark model, Dick Dalitz, to take up a research fellow position at All Souls College in 1993. Mike's distinctive approach used the lattice method to unfold the inner workings of QCD, to question how it manages to confine the quarks and the gluons. His work is characterised by clarity and elegance of argument, coupled with a painstaking and rigorous approach to accuracy. His work on how the string tension depends on the number of colours, the N-ality of the string, and string excitations (to name but a few), has been influential way beyond the lattice QCD community. Apart from the physics of QCD, Mike has contributed significantly to algorithm development, improving the precision and efficacy of lattice analyses. Several former students and postdocs will speak at a symposium in his honour on 24 November (2:00–5:30pm in the Dennis Sciama lecture theatre, followed by a reception in the Dalitz Institute).

AWARDS



PROF STEVE BALBUS has been elected to the Fellowship of the Royal Society in recognition of his ground-breaking work in astrophysical fluid dynamics.

PROF JO DUNKLEY has been awarded the Royal Society Rosalind Franklin Award 2016 for her research on the Cosmic Microwave Background and her innovative project to support and encourage girls studying physics.

PROF ANDRE LUKAS has won the OUSU Most Acclaimed Lecturer in MPLS award. These student-led awards provide students with direct opportunities to recognise excellence in teaching.

PROF TIM PALMER was awarded an Honorary Doctorate Degree by the University of Bristol.

PROF HENRY SNAITH FRS has been awarded the Royal Society Kavli Medal and lecture. This award is made for excellence in all fields of science and engineering relevant to the environment or energy. Henry receives this award for his 'discovery and development of highly efficient perovskite solar cells which promise to dramatically increase the efficiency and reduce the cost of solar energy'.

PROF CAROLINE TERQUEM has won an MPLS Teaching Award for her outstanding teaching of the second year electromagnetism course.

DR SAM VINKO was awarded the IUPAP Young Scientist Prize in Plasma Physics in recognition of his 'seminal contributions in using the world's first hard X-ray free electron laser to create and diagnose solid density plasmas, and for new insights into the electronic structure and collisional dynamics of such systems'.

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