HERIOT WATT UNIVERSITY

Physics Department Newsletter

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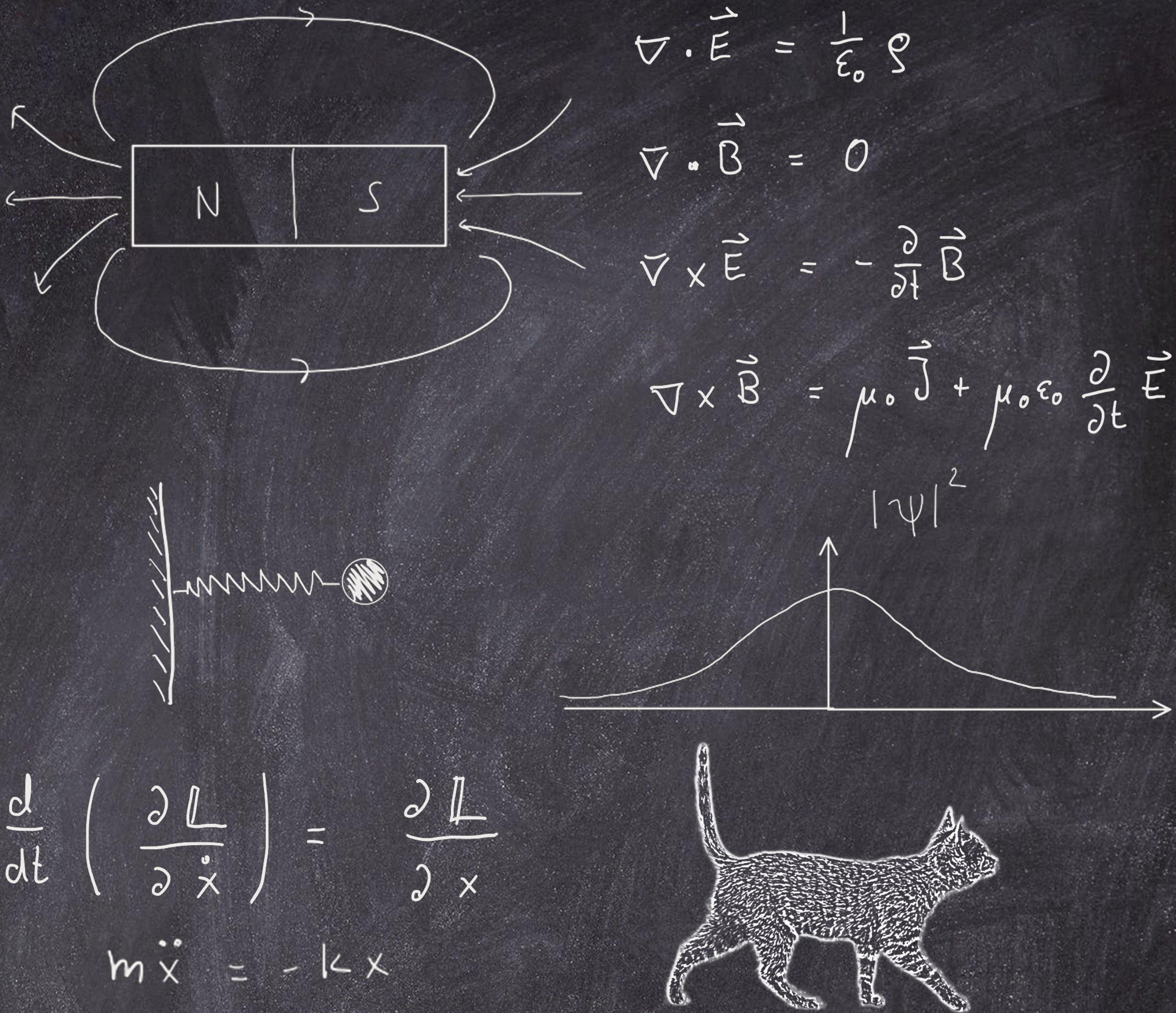

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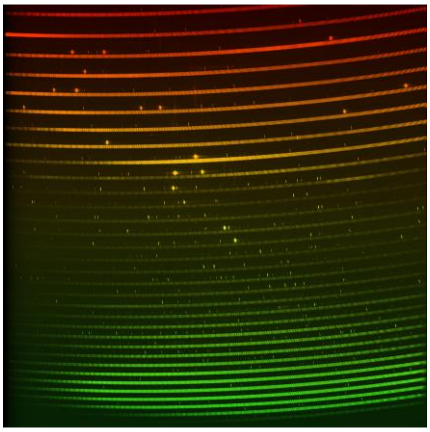
Ultrafast Lasers Reaching For The Stars

Prof. D. T. Reid, Reid Group & Dr. R. McCracken



One of the most exciting scientific fields to open up in the 21st century is the discovery of exoplanets, those planets which are orbiting a host star outside our solar system. Wider recognition of the field came with the award in 2019 of the Nobel Prize for Physics to Michel Mayor and Didier Queloz for their discovery in 1995 of the first confirmed exoplanet orbiting the star 51 Pegasi.

There are three main ways to detect exoplanets. The transit method -- used by NASA's Kepler space telescope -- looks for small dips in the light intensity from a star as an orbiting planet "transits" across the field of view between its host star and an observer. Over 4000 exoplanets have been detected by Kepler in this way, but the technique cannot reveal information about the planet's mass. For this, another ground-based technique is used, known as radial velocity (RV) measurement.

The RV concept is simple. Consider some alien solar system containing a single planet orbiting a star. These two objects in fact orbit their common centre of mass, meaning that the planet's orbital period is also imprinted onto small movements of the star. These movements can be detected by telescopes on Earth by observing tiny Doppler shifts in the wavelength of the light emitted by the star. The characteristic hydrogen spectrum of absorption lines that is present in star light provides a pattern, whose periodic shift to longer and shorter wavelengths tells us about the orbital period and mass of the exoplanet.

The emphasis today is on finding exoplanets that could support life, those occupying the so-called habitable zone (or Goldilocks zone ... not too hot, not too cold!). This restricts the hunt to looking for quite small planets orbiting quite big stars, just like the Earth and the Sun, but for these the Doppler shift written onto the star light is very small -- of order 10-10. Detecting such a tiny wavelength shift requires a very sensitive and very stable spectrograph, and Prof. Derryck Reid's group are part of a UK consortium contributing such instrumentation to the planned Extremely Large Telescope, currently under construction in the Atacama Desert in Chile.

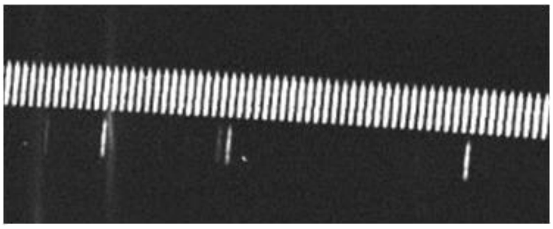
An astronomical spectrograph provides a spectrum of the light from a star, formatted as a 2-D image on a photon-counting CCD camera. Each pixel of such a CCD array samples a small frequency bandwidth of the light -- typically around 2 GHz (remember, the frequency of visible light is about 500 THz). But the shifts astronomers need to see are much smaller still, around 100 kHz, and correspond to movements of the spectrum across the CCD array of less than the diameter of an atom.

Since no spectrometer can maintain that precision indefinitely, an external calibration source is needed, and it is here that lasers play a role. Phase-stabilised femtosecond lasers provide perfectly periodic pulses in time. When considered in the frequency domain, these pulses form a sequence of exactly spaced frequencies known as a 'frequency comb', which can act as a ruler for optical frequency. By rigidly locking the spacing of the comb lines to an atomic reference, frequency combs can be produced that maintain the same optical spectrum over decades, allowing astronomers to use them as a calibration reference for high precision spectrographs.

Precision calibration allows the data from spectrographs to be correlated over many weeks of observations, allowing radial velocity data to be built up over the timescale needed to observe the orbital period of a distant planet. But beyond this it

The astrocomb demonstrated at SALT in 2016 sat on a precisely calibrated 'laser desk'. We have been promised more robust infrastrucrure for the astrocomb we hope to install in 2022!

allows observations to be correlated over decades, enabling potentially astronomers to look for tiny variations in the expansion rate of the universe, which could reveal changes in the values of fundamental constants like the fine structure constant.



An astrocomb (top row) provides a series of equidistant markers on the spectrograph CCD, greatly increasing the calibration precision. Older calibration methods such as ThAr emission lamps (bottom row) vary in brightness, spacing and linewidth.

Working with Dr Richard McCracken, Reid and his group are building astrocombs -- lasers that produce widely spaced comb lines (10 - 20 GHz) across unprecedented bandwidths. For the ELT, the astrocomb must cover 370 - 2400 nm, which far exceeds the range ever before demonstrated. New nonlinear techniques such as phase-coherent optical parametric oscillators now make it possible to approach this kind of performance. McCracken and Reid already demonstrated one such astrocomb on the SALT telescope in 2016, and are now working with teams from the ELT, SALT and INT to deploy future astrocombs on spectrographs in these telescopes.

Fast Optical Sampling Using a Single Mode-Locked Laser

Dr. David Bajek & Dr. M. A. Cataluna

Measuring ultrashort temporal events: What happens in the blink of an eye? It is an age-old question! The limit of huge structures in the dimension of space, such as the size of the universe itself, invoke fascinating questions. But equally as fascinating are the temporal equivalent – how long do events occur? Events such as the formation of stars or the age of the Universe. At the other end of the scale, we are just as fascinated by the smallest microscopic organisms, right down to subatomic particles and beyond. And so, just as importantly, we are fascinated with ultra*short* temporal events – when did we find out the rate at which a hummingbird flaps its wings? What about the first recorded frames of a bullet leaving a gun?

Advances in lasers and ultrafast photonics have meant that optical sampling techniques have wide applications across physics, chemistry, and biology. These are usually arranged where two trains of ultrashort pulses are interfered with each other to measure temporal events or ultrashort processes occurring within them. For example, pump-probe spectroscopy is used within biophotonics to characterise important biological processes which occur over such short time frames (picoseconds to femtoseconds). So short that conventional cameras, even with the fastest shutter speeds, would struggle to capture. Instead, by framing an event of interest between two light pulses, we can build the microscopy equivalent to a camera using just pure, pulsed laser light – such as in fluorescence lifetime imaging (FLIM). The same ideas are applicable to chemical and physical processes, where the birth of femtochemistry and attoscience were facilitated by pulsed lasers, capable of measuring ultrashort events, such as the breakdown of individual chemical bonds.

Pump-probe spectroscopy techniques today often employ either a single-laser system with mechanical parts (e.g. delay stages, OSCAT), or use two-lasers in a non-mechanical system (e.g. ASOPS, ECOPS). The former can be slow, bulky, and subject to vibrational noise and stability-related inaccuracies. The latter may avoid these problems but comes at twice the cost and twice the complexity. OSBERT (Optical Sampling By Electronic Repetition Rate Tuning) takes advantage of two-section passively mode-locked lasers to bridge the gap between both these drawbacks. Since the laser can be electronically manipulated we can mitigate the need for any moving parts in one fell swoop while using only one laser.

As a proof of principle, we tested our new technique within metrology, distance measurements of a moving target. Whilst we did so at an impressive 1kHz scan rate (that's 1000 scans per second), we have recently had our work accepted at CLEO in San Jose this year, demonstrating scans at 1MHz, along with a further study on an alternative design called SLASOPS (Single Laser Asynchronous Optical Sampling). For both these techniques, the future is bright, where their deployment in pump probe spectroscopy could be a low-cost, compact, and innovative solution in an otherwise expensive, bulky, and complicated optical sampling world. We are also excited to have one of our students, Ife Ejidike, join us as an AWE-sponsored summer researcher this year, who will be simulating some of the rather interesting things which happen to light pulses when they are manipulated in this manner.

To read more: https://doi.org/10.1364/OE.413045

Launching into 'Space' – Watts-Up

Kate Robertson, 5th Year Mhys Chemical Physics

At the beginning of the last academic year, a group of around 20 students from the department set out on an ambitious task – to launch a high-altitude weather balloon into the upper atmosphere. Led by Kate Robertson, Ross Urquhart and Seb Roberts, (and with support from the department secured) interviewing candidates for the various leadership roles began. These are payload design and manufacturing (Callum Cox), statistics and logistics (Prab Singh) and Programming and automation (Johnnes Walter).

Our mission was to work with the department to launch a weather balloon into 'space' and collect data with various sensors – possibly even contributing to some research within the department. Great progress was made in the 2019/20 academic year, with potential launch sites identified and all necessary paperwork in the progress of being completed. Although choosing and obtaining weather balloons was straight forward, getting our hands on the helium to fill them was not! Thankfully, the department managed to acquire some, and we could move onto the next stage of testing the design. A protype payload was constructed along with the programming of the sensors. Unfortunately, with only weeks to go until the first test launch, Covid-19 brought everything to halt.

'Weightless', seamlessly floating in mid-air – the team admire the underlying principle behind the project.

Left to Right: Callum Cox, Prab Singh, Seb Roberts, Ross Urquhart and Johannes Walter

The team is looking forward to picking things up once we return to 'normal' and forging ahead with testing and launching the prototypes. Of course, some of us will be graduating this year and that means there will be plenty of opportunity for other students to get involved!

If you are interested, then please email Kate Robertson or get in touch with the Physics Society on Teams.

Shared Experiences – Life After Graduation

Sean Keenan, 5th Year Mphys

One thing all undergraduates have in common, or have experienced at some point in their studies, is a feeling of uncertainty and anxiety about the future. Okay, let's be honest, I think everyone has that feeling at least once in their life (more so with the current pandemic)! It is difficult to know what you want "to do" with your degree, never mind what to do when things do not turn out the way you expected. I certainly speak from experience, and I still don't really know what I want to be when I "grow up" (he says on the cusp of turning 30…)

There is something rather unique about the paralysis of choice – those situations where you must choose something, like which assessment to prioritise, but you have doubts or feel unsure – ultimately procrastinating and 'just doing nothing'. It is something I feel we have all experienced as undergraduates; trying to find the motivation to make deadlines while maintaining some form of social life and keeping up hobbies and the like.

But to what end? What is the goal after I graduate? I know it is a question that plagues most of us.

With that in mind, I wanted to collect the experiences of those who have graduated from Heriot-Watt – a sort of 'where are they now' section. The idea is to give perspective on the opportunities out there once you graduate and share the different experiences people have while studying.

Jake Sanwell very kindly agreed to answer some questions for this inaugural section.

What inspired you to get into Physics?

It's what I enjoyed the most in school and consequently, was my best subject. I've always taken great pleasure in applying knowledge to solve problems and that's exactly what physics allowed me to do. Also, I really like building things, so the engineering side of it was particularly appealing. There is a distinct memory from our school trip to CERN of seeing the ATLAS detector for the first time and being astounded by the sheer number of wires going into it. I don't know if I'd call it hugely inspiring, but it certainly piqued an interest in applied physics/engineering.

What is your current role and what steps did you take to get there?

I recently started a PhD with Daniel Esser in the Laser Device Physics and Engineering group at Heriot-Watt. Getting to where I am today has mostly just been a case of taking what comes my way and sounds both challenging and fun – which is something I feel quite lucky to say. At the end of school, I knew I liked physics and engineering so, I applied for a degree in Engineering Physics.

During my degree I found that problem solving was something that came very naturally to me, and Daniel's [Prof. D. Esser] problem solving class was one of my favourites. Daniel had also been my academic mentor since 1st year, and my 4th and 5th year project supervisor. So, when I was

Jake Sanwell is currently working on his PhD with the Laser Device Physics and Engineering group under Prof. Daniel Esser.

offered a PhD position where I would be using physics and engineering to solve problems, with a supervisor I already knew I worked well with and with colleagues I knew I got on with, it seemed like quite a good deal.

I didn't accept right away and kept my eye out for other opportunities for a while, but eventually I decided to just go for it.

What is your favourite part of your current work / what do you find most interesting about physics?

Laser development is not where I expected to end up considering that I was never a huge fan of optics in the first place. The design and testing of these systems are what really appeals to me. I have to incorporate fluid mechanics, electronics, chemistry, software development, and materials science in with the optics and that's where the real fun is. My favourite part has always been bringing everything together, getting my hands in and making useful, life size stuff. I've never really been one for micro-scale quantum mechanics or universal-scale astronomy.

It's all been pretty interesting. Suppose I just need more hours in the day. Also, there's a lot of reading sometimes. I don't like reading very much.

What do you enjoy most about your current work?

So far, I've had the most fun designing parts and software. I get a lot of enjoyment trying to iteratively find the optimal solution to a problem and both of those processes involve just that. I'm looking forward to being able to actually make systems with said parts, but I haven't got to that stage yet.

How has your degree helped you in your current role / what has been the most useful aspect of your degree?

The most useful thing I've learned is how to learn things. Whatever you do after uni, you will have to learn new skills for it, so the ability to learn is hugely valuable. This is something you can get from almost any degree, but there is a specific mindset you get from physics that I am very appreciative of.

Has your degree in physics helped you in any way that isn't explicitly linked to science?

The way I tackle life is very similar to the way I tackle physics questions and I think they've both had an influence on each other. I can't think of anything specific, but the degree has definitely taught me that you will become good at anything you invest time in. Spending time doing anything like studying, playing music, socialising, or relaxing will improve your understanding of those things. We all only have so much time in our days so, it's important to think about where you want to invest it.

What were / are the biggest challenges in your degree / career so far?

I think motivating and managing yourself is the hardest part of any degree. It's something I figured out quite early on, but I definitely had to keep an eye on it. Making sure you work effectively is important but relaxing effectively is important too! You can't focus properly if your head is constantly in gear.

Is there anything you dislike about physics / disliked in your degree?

Honestly, it went quite well for me, so I don't have many criticisms. I would have liked to get more hands-on experience with things like building circuits or machining parts, but I don't think there's anything I've done that I'd replace with those things.

If there was one piece of advice you wish someone gave you in first year – what would it be?

Just go to as many lectures/tutorials/labs as you can. Doesn't matter if you don't think you're getting anything from them. Doesn't matter if you're barely awake. Doesn't matter if you're already behind and it really doesn't matter if most of your pals don't go. You will pick up more than you realise just through exposure and it'll save you a huge amount of stress later down the line. All courses are more enjoyable the more you engage with them. Do whatever you want after your lectures. Go to everything.

List of Latest Research Output

Imperfect 1-out-of-2 quantum oblivious transfer: Bounds, a protocol, and its experimental implementation
Amiri, R, Stárek, R, Reichmuth, D, Puthoor, IV, Mičuda, M, Mišta, L, Dušek, M, Wallden, P & Andersson, E.
In: PRX Quantum, vol. 2, no. 1, 010335. https://doi.org/10.1103/PRXQuantum.2.010335

Fast optical sampling by electronic repetition-rate tuning using a single mode-locked laser diode
Bajek, D & Cataluna MA.
In: Optics Express, vol. 29, no. 5, pp. 6890-6902. https://doi.org/10.1364/OE.413045

Laser-frequency-comb calibration for the Extremely Large Telescope: an OPO-based infrared astrocomb covering the H- and J-bands
Cheng, YS, Xiao, D, McCracken, RA & Reid, DT.
In: Journal of the Optical Society of America B: Optical Physics. https://doi.org/10.1364/JOSAB.421310

Towards combined quantum bit detection and spatial tracking using an arrayed single-photon sensor
Donaldson, R, Kundys, D, Maccarone, A, Henderson, R, Buller, GS & Fedrizzi, A.
In: Optics Express, vol. 29, no. 6, pp. 8181-8198. https://doi.org/10.1364/oe.416143

Emergence of the circle in a statistical model of random cubic graphs
Kelly, C, Trugenberger, C & Biancalana, F.
In: Classical and Quantum Gravity, vol. 38, no. 7, 075008. https://doi.org/10.1088/1361-6382/abe2d8

Compressive coded rotating mirror camera for high-speed imaging
Matin, A & Wang, X.
In: Photonics, vol. 8, no. 2, 34. https://doi.org/10.3390/photonics8020034

Optimised domain-engineered crystals for pure telecom photon sources
Pickston, A, Graffitti, F, Barrow, P, Morrison, CL, Ho, J, Brańczyk, AM & Fedrizzi, A.
In: Optics Express, vol. 29, no. 5, pp. 6991-7002. https://doi.org/10.1364/OE.416843

Semi-device-independent random number generation with flexible assumptions
Pivoluska, M, Plesch, M, Farkas, M, Ružičková, N, Flegel, C, Herrera Valencia, N, McCutcheon, W, Malik, M & Aguilar, EA.
In: npj Quantum Information, vol. 7, 50. https://doi.org/10.1038/s41534-021-00387-1

Avoiding gauge ambiguities in cavity quantum electrodynamics
Rouse, DM, Lovett, BW, Gauger, EM & Westerberg, N.
In: Scientific Reports, vol. 11, 4281. https://doi.org/10.1038/s41598-021-83214-z

Exchange-free computation on an unknown qubit at a distance
Salih, H, Hance, JR, McCutcheon, W, Rudolph, T & Rarity, J.
In: New Journal of Physics, vol. 23, no. 1, 013004. https://doi.org/10.1088/1367-2630/abd3c4

Metalens for Generating a Customized Vectorial Focal Curve
Wang, R, Intaravanne, Y, Li, S, Han, J, Chen, S, Liu, J, Zhang, S, Li, L & Chen, X.
In: Nano Letters. https://doi.org/10.1021/acs.nanolett.0c04775

Soliton evolution and associated sonic horizon formation dynamics in two-dimensional Bose-Einstein condensate with quintic-order nonlinearity
Wang, Y, Chen, Y, Dai, J, Zhao, L, Wen, W & Wang, W.
In: Chaos, vol. 31, no. 2, 0031741. https://doi.org/10.1063/5.0031741

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