The year 2014 ended with the announcement of the Research Excellence Framework results, an important exercise in which all UK universities are assessed on their research activities, and on which funding allocations are then based. The Department formed the bulk of UCL’s ‘Physics’ submission, with major contributions also from our colleagues in the London Centre for Nanotechnology and in the Mullard Space Science Laboratory.

It is possible to make all kinds of different league tables from the results, but the ones that count most are those which correlate closely with the funding. On all of these, UCL Physics was in the top five nationally, and on my favourite – “research intensity”, or average grade per academic – we were second (to Cambridge, so well done them too). These results are of course based primarily on the great research being carried out in the department, and you will find many examples of that throughout the review.

Another success, prepared in 2014 but announced in February 2015, was our receipt of the Institute of Physics Juno (and subsequently Athena Swan) award. These schemes are aimed at addressing the systematic gender imbalance in physics, which is a very important issue for the field. However, I found the lessons they teach about transparency and clarity of organisation, and improving the working environment for all, very generally applicable. I believe our department will be fairer, more pleasant and more successful as a result, to the benefit of all of us. Winning recognition for our efforts is nice, but it the process continues and there is still much work to be done.

The tragic death of Bruce Swinyard in May 2015 was a great loss, and our thoughts are with his family. A full obituary appears on page 13.

Several members of the department received prizes in 2014: Benjamin Joachimi and Ofer Lahav won awards from the Royal Astronomical society, as did the Herschel and Cassini teams which have several UCL members. David Walker won the IoP Optics and Photonics prize, Angela Occhigrosso and Jennifer Chan won the faculty postgraduate research and taught course prizes, respectively. Steve Fossey won the UCL Communications and Culture award (remember the supernova discovery in Messier 82 from the last review!), Matthew Wing won the Friedrich Wilhelm Bessel Research Award from the Humboldt Foundation, Gerhard Materlik won the IoP Glazebrook medal, and Ian Robinson won the Aminoff Prize.

We are surrounded by major estates works, in the Physics Yard and the Kathleen Lonsdale Building; the astrophysics group are currently working in temporary accommodation in Hampstead Road. The financial environment in UCL is also challenging at present, as the university tries to build up a sustainable surplus to reinvest in the future. However, the department is strong and confident. We will meet these challenges together, and continue to prosper.
Training the next generation of physics teachers

An important development for the Department’s teaching programme has been a new collaboration with the Institute of Education (IOE) to set up a Physics (BSc) plus Qualified Teacher Status (QTS) degree. All BSc students in our Department (including Physics, Theoretical Physics and Astrophysics) will from 2016/17 be able to opt-in for the QTS pathway during Year 3 of their BSc, and spend an extra year on the IOE run QTS qualification.

As a taster of physics education and teaching, a 5-day summer experience will be open to all Year 1 and Year 2 students in June/July 2016, at the IOE and with days in a partnership secondary school.

The UCL Physics plus QTS degree will be supported by bursaries and other maintenance allowances. We anticipate that this exciting new opportunity will lead to several students taking up careers as physics teachers in school each year.

By Raman Prinja

Quantum mechanics explains efficiency of photosynthesis

Light-gathering chromophores in plant cells transfer energy by taking advantage of molecular vibrations whose physical descriptions have no equivalents in classical physics, according to research by physicists in UCL’s AMOPP group.

Molecular vibrations are periodic motions of the atoms in a molecule. When the energy of a collective vibration of two chromophores matches the energy difference between the electronic transitions of these chromophores a resonance occurs and efficient energy exchange between electronic and vibrational degrees of freedom takes place.

Providing that the energy associated to the vibration is higher than the temperature scale, only a discrete unit or quantum of energy is exchanged. Consequently, as energy is transferred from one chromophore to the other, the collective vibration displays properties that have no classical counterpart.

The team found the signature of non-classicality is given by a negative joint probability of finding the chromophores with certain relative positions and momenta, something impossible in classical physics.

Published by E. O’Reilly and A. Olaya-Castro, Non-classicality of the molecular vibrations assisting exciton energy transfer at room temperature. Nature Communications, 5 (2014)
Twinkle: a new mission to study exoplanets

A new satellite for observing extrasolar planets could be in orbit within four years, under plans drawn up by UCL and Surrey Satellite Technology Limited (SSTL). The Twinkle satellite, pictured below, will observe the light of distant stars with planets orbiting them.

As a planet passes between the star and Twinkle’s telescope, a small amount of the light passes through its atmosphere, imprinting on it the chemical signature of its atmosphere. This technique has been used by Hubble to analyse the atmospheres of a handful of exoplanets, but the Twinkle team hopes to probe at least 100 during the spacecraft’s mission.

Giovanna Tinetti is the lead scientist in a consortium of UK institutes who will construct Twinkle’s scientific instrumentation, a highly precise infrared spectrometer which can tease out the faint signature of the planetary atmospheres from the starlight.
Engineering without borders: Physics student in UCL News

Gabriela May Lagunes, an undergraduate student in Physics and Astronomy, has used her skills to help improve quality of life in poor communities in Mexico. She is a member of UCL’s branch of Engineers Without Borders (EWB), an international organisation that creates change by empowering engineering students to work in international development.

Gabriela coordinated a project that installed and repaired 13 rainwater-harvesting systems in the schools and clinics of eleven different communities in the Mexican city of San Miguel de Allende last summer.

“The project was very important as the levels of fluoride and arsenic in this particular area are between five and ten times higher than the international norm, often leading to health issues such as fluorosis, renal insufficiency and cancer from an early age,” she says.

“Gabriela coordinated a project that installed and repaired 13 rainwater-harvesting systems in the schools and clinics of 11 different communities.”

Students in action

What is the mass of the neutrino?

Do neutrinos have mass? And if so, how much? This apparently simple question has no simple answer and has been the subject of debate, controversy and confusion in the world of physics in recent years.

The consensus among physicists is that the standard model of particle physics is incomplete – but identifying what is missing from it is a complex issue.

Cosmologists are currently trying to get to the bottom of this question, with sometimes quite radical solutions. Boris Leistedt and Hiranya Peiris, two UCL researchers, have recently ruled out one of these eye-catching theories, the idea that neutrinos have a relatively high mass.

They look at this apparent evidence for high-mass neutrinos from two different angles:

• First, if the neutrino is indeed heavy, what would that imply about the universe around us (and does it fit with what we see)?
• Second, if it is not, what else could explain the discrepancies in the data?

On both fronts, their analysis points firmly at a significantly lighter neutrino, in line with previous estimates. They argue that the distribution of galaxies in the universe is only compatible with a low-mass neutrino, and that the discrepancies in the data that hinted at high-mass neutrinos are down to imprecise measurements of galaxy clusters.


Bioengineering for everyone

A startup led by two astrophysics PhD students is making waves in the world of biotechnology. Tom Catling and Olly Coles are co-chief technology officers of Bento Bio (previously known as Darwin Toolbox), which is developing a lab-in-a-box for DIY science projects. The kit, currently undergoing testing, is a safe, affordable and easy portable biology laboratory including a centrifuge and DNA analysis kit.

Their work has been recognised with a win in the London Entrepreneurs Challenge and UCL Bright Ideas award, as well as a runner-up place in the Royal Academy of Engineering’s Enterprise Hub scheme. They’ve also been covered on BBC Radio and in technology magazine Wired.

They now have their own CNC machine and are building up a nice collection of tools, as well as securing a loan from UCL to rent a workshop.

Plans for the immediate future are to produce more prototype boxes and distribute them around the community to get some feedback on how people use them. They hope soon to start outsourcing construction.

The team are also keen on public engagement, travelling to the Green Man Festival to present their ‘bacterial art’, and won £2000 thanks to an audience vote at UCL Public Engagement Unit’s Focus on the Positive competition.

What is the mass of the neutrino?

UCL physicists weigh in

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Atmospheres of exoplanets throughout history have been a fascinating subject of study. From the age of eleven, I have been interested in the atmospheres of extra-solar planets (now simply known as exoplanets) ever since I knew they existed. From the age of eleven, I have been trying to understand these planets, but it was only at university that I realised how sophisticated a challenge this was. During my undergraduate and masters in Astrophysics at the University of Edinburgh, I followed the development of exoplanetary research as it progressed, and I became the coordinator for the mission’s educational programme, EduTwinkle. It aims to bring space exploration into schools and improve the uptake of STEM subjects amongst women and other underrepresented groups.

In early 2015 I joined Twinkle; a new space mission dedicated to the study of the atmospheres of extra-terrestrial worlds, led by Giovanna Tinetti. Given my interests in outreach and astrophysics, I became the coordinator for the mission’s educational programme, EduTwinkle. I have wanted to work with extra-solar planets ever since I knew they existed.

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The second Physics and Astronomy Gala Dinner was held on the 24th of October 2014, in the nearby Ambassador Hotel (as the Wilkins Building is undergoing extensive refurbishment). Some 30 undergraduate and postgraduate prize winners and their guests, 18 members of staff and 57 alumni – an unprecedented number – came together to meet at the reception. Over dinner, they heard about our students’ achievements in the award ceremony, and then heard the traditional after dinner speech.

Chris Lintott (UCL PhD 2006) gave this year’s speech. Fresh from being appointed to his professorship in Astrophysics and Citizen Science at Oxford, Chris is famous as one of the presenters on BBC Sky at Night. Chris related the previous January’s discovery of the supernova in Messier 82 by four of our undergraduates assisted by Steve Fossey, comparing it to perhaps the first example of large scale public participation in the history of astronomy: when the total eclipse of the sun was observed and reported by many citizens across England and Wales in 1715. Edmund Halley had predicted the path of the total eclipse across the country (Phil. Trans. R. Soc. Lond. April 1715) but did not live long enough to check his predictions when the eclipse occurred again in 1724.

Following a stellar career at Oxford, Durham, Cambridge and Caltech, Prof Richard S Ellis CBE FRAS is returning to his Alma Mater at UCL. I am proud to announce that he will be the After Dinner Speaker at the third Gala Dinner and Prize Giving to be held on Friday 23rd October 2015.

By Professor Tegid Wyn Jones

Exoplanet research in the mid 20th century was driven by the desire to work at UCL, knowing she was doing extraordinary work into exploring far away worlds with these exact techniques. Giovanna suggested that I contact Jonathan Tennyson, then the head of the Department of Physics & Astronomy, to discuss joining his team who were pioneering the modelling of molecules in space. As a result, in 2011 I joined his ExoMol project as a PhD student.

With a talented multidisciplinary team of chemists, physicists, astronomers and computer scientists, ExoMol is creating a comprehensive molecular database for the atmospheric characterisation of exoplanets. My PhD focused on simulating molecular spectra for phosphine, which would enable the remote identification of this molecule on exoplanets. Due to its biogenic origins, phosphine is a potential marker for extinct or existing extraterrestrial life.

On Earth, it also happens to be an unintentional marker for crystal meth labs. While writing up my PhD, I joined Researchers In Schools - a new teacher training programme for post-doctorate scientists aiming to bring exciting new research in to secondary schools. With the support of the programme’s organisation, the Brilliant Club, and my business sponsor Goldman Sachs, I have taught science in several London schools and currently work part-time at Highams Park School.

I am currently organising a EduTwinkle project where young astrophysicists supervise A-level students so they can produce original, publishable research alongside their studies. Many more projects for all age groups are being developed and these will continue until after the spacecraft launch in late 2018. My research with phosphine and other molecules has been published at several leading astrophysics journals and I have spoken at major scientific conferences and educational events, most recently at the Royal Astronomical Society and Downing Street.

By Clara Sousa Silva

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The atmosphere of the Earth contains far less xenon (the second heaviest noble gas) than expected. It is one of the enduring mysteries of the planetary sciences and is often referred to as the ‘missing xenon paradox’. Combining advanced structure prediction techniques, and high quality quantum mechanical calculations, the research team have shown that at the pressures found in the Earth’s core both iron and nickel (its main constituents) react readily with xenon to form a variety of thermodynamically stable compounds – most importantly the cubic Fe3Xe (see Figure). Using diamond anvil cells, the conditions at the centre of the Earth can be reproduced in the laboratory. Experiments which have tried to make iron xenon compounds have never been successful, and earlier calculations made assumptions about the likely structures and found no bonding. It had been concluded that iron and xenon do not react in the Earth’s core.

Advances in structure prediction (such as ab initio random structure searching, developed by Prof Chris Pickard, and swarm based approaches pioneered by Jilin researcher Prof Yanning Ma) allow the unbiased discovery of unexpected materials. New, more stable, xenon iron compounds were found in the current study, and the earlier conclusion overturned. Awaiting experimental confirmation of the result, their article published in Nature Chemistry proposes that the Earth’s core is a natural hiding place for the missing xenon.

C. Pickard et al, ‘Reactions of xenon with iron and nickel are predicted in the Earth’s inner core’, Nature Chemistry, 6, 2014

Cubic Fe3Xe. At sufficiently high pressure (around those found in the Earth’s inner and outer cores) the normally inert xenon reacts readily with iron and nickel.
This year the department has employed an Outreach coordinator for the first time. This is to coordinate all of the outreach currently being done by members of the department, but also to build better relationships with nearby schools by forming Physics Partnerships, and to invigorate and improve the outreach program offered through the University of London Observatory (ULO).

Since beginning my role at the very end of July, a day after leaving my previous role as a physics teacher, I have been investigating various ways in which I can help make the outreach that the department conducts more sustainable. At the top of this list is building partnerships with schools, where we offer more than just appearances at one-off events. So far this program is shaping up to include lunchtime lectures from undergraduate students, CPD training for teachers, teaching internships for undergraduate students, and talks from academics on a wide range of topics from careers to the more inaccessible areas of the A-level curriculum.

With regards to ULO I have begun to learn how the current system of school and public tours operate and to see how we can deliver the largest impact. Combining my astronomy and teaching backgrounds I am exploring different methods that we can use to deliver our Schools Programme. One such option is for the department to invest in a mobile planetarium that can be taken into schools for children of all ages to experience the wonder and amazement that only comes from viewing a completely dark night sky – a nearly impossible task for the thousands of schoolchildren who live in central London!

We have also been working hard to raise the profile of ULO on the UCL campus. We arranged a display of astronomical images taken at ULO in the South Cloisters complete with an information board describing the history of the Mill Hill site. The images cover a wide range of celestial objects including the Type Ia Supernova SN2014J discovered by undergraduates and Dr Steve Fossey during an evening observing session.

We also held a pop-up event out of the Northern Dome in the main quad with the aid of UCL Museums and Mathematical & Physical Sciences Faculty staff. Over 250 visitors enjoyed observing the sun through a solar scope, viewing Lunar Orbiter, Viking and Mariner archive images of the Moon and Mars taken during the 1960s and 1970s, and learning about the advancements in astronomical images from the Palomar Sky Survey in the 1950s to the Hubble Space Telescope images taken today.

By Sarah Hutton
## Academic Appointments

Recruitment is a two-way process, and a measure of the continuing success of the Department can be evidenced through the ability to attract highly esteemed academic members of staff. Each member of staff complements and enhances the high-profile research portfolios of both the individual research groups and the Department as a whole.

### Promotions

**Promotion to Professor**

Prof. Peter Doel (Astro)
Professor of Astronomical Instrumentation

**Promotion to Reader**

Dr David Cassidy (AMOPP)
Reader in Physics

Dr Stephen Hogan (AMOPP)
Reader in Atomic and Molecular Physics

**Promotion to Principal Teaching Fellow**

Mr Paul Bartlett
Principal Teaching Fellow

**New academic members of staff**

Dr Mark Ellerby (CMMP)
Principal Teaching Fellow

Mr Paul Bartlett
Principal Teaching Fellow

Dr Emily Nurse (HEP)
Reader in Atomic and Molecular Physics

Dr Stephen Hogan (AMOPP)
Reader in Physics

Dr David Cassidy (AMOPP)
Promotion to Reader

Dr Emily Nurse (HEP)
Promotion to Reader

### Retirements

Dr Mark Ellerby (CMMP)

**In memoriam**

Bruce Swinyard

The department has lost a dear friend and colleague.

Bruce Swinyard joined the Department of Physics & Astronomy’s Astrophysics Group in the summer of 2010, as a joint appointment between UCL and STFC’s Rutherford Appleton Laboratory, spending half his time at UCL and half at RAL’s Space Science and Technology Department, where he was Leader of the Astronomy Group.

Bruce played an outstanding role in the successful development of a series of state-of-the-art scientific instruments for important space missions. He was Calibration Scientist for the Long Wavelength Spectrometer for ESA’s Infrared Space Observatory, which flew between 1995 and 1998. From 1999 he designed and oversaw the technical development of the SPIRE imager and spectrometer for ESA’s Herschel Space Observatory, to its launch in 2009 and the completion of its ground-breaking mission in April 2013. He was deeply involved in the use of the SPIRE instrument in orbit and devised a number of innovative observing techniques that successfully stretched its capabilities. In particular he recognised before launch the potential power of using Herschel’s two multi-wavelength imaging instruments (SPIRE and PACS) as effectively a single ‘fourth instrument’ when operated in ‘parallel mode’. This enabled a number of high impact observing programmes, including deep surveys for extragalactic sources and the HIGAL survey of the plane of the entire Milky Way.

From 2001 until 2005, Bruce acted as European Project Scientist for the James Webb Space Telescope’s MIRI instrument. He then stepped down from that project in order to concentrate on his role as the European Principal Investigator for the Japanese-led SPICA infrared mission, in particular leading the design of the proposed European SAFARI instrument. Bruce then led the conceptual design and modelling of the integrated payloads for the proposed ECHO, Ariel and Twinkle exoplanetary transit spectrometry missions. He was one of the leaders of an initiative to involve industry in the design and implementation of innovative receiver technology in space, which led to the recent funding of the LOCUS supra-THz limb sounding instrument to measure atomic oxygen and other species in the Earth’s upper atmosphere.

Bruce was first diagnosed with cancer nearly four years ago but continued to work normally and in his usual optimistic way, continuing to generate many new ideas for instruments and missions. Unfortunately Bruce’s health began to decline rapidly earlier this year, and he passed away on 22 May 2015.

Bruce was an inspiration to the many colleagues and students that he worked with. He was an incredibly brave and talented person and his death represents a major loss to the Astrophysics Group and to the Department of Physics and Astronomy.

Our thoughts are with his wife Margaret and his two daughters.

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**LHC may falsify Leptogenesis**

From experiments we know that there is an asymmetry of matter and anti-matter in our universe. The excess of baryons over anti-baryons (e.g. protons over anti-protons) could be triggered by a mechanism called leptogenesis, which is currently the most favourite explanation for many particle physicists.

Already in 1967 Sakharov defined three conditions which such models have to fulfil. One of them is the departure from thermal equilibrium. This is a crucial condition as in thermal equilibrium any net baryon asymmetry produced by a specific process would be immediately destroyed by the inverse process. This is usually called “wash-out”.

Now Frank Deppisch and Julia Harz (HEP group) have demonstrated that it is possible to draw conclusions from observations at the LHC on the evolution of the universe: observing a process which violates lepton number at the LHC is equivalent to establishing a lower limit on the washout factor for the lepton number in the early universe.

If the primordial lepton number asymmetry is originally generated above the lepton number violating scale observed at the LHC, the resulting washout will reduce the asymmetry exponentially, rendering leptogenesis ineffective. Thus, the LHC may offer a unique way to rule out leptogenesis.

Royal Swedish Academy of Sciences: Gregori Aminoff Prize in Crystallography
Awarded to Professor Ian Robinson
For his contribution in areas concerned with the dynamics of the formation and dissolution of crystal structures, specifically his pioneering contributions in the field of X-ray diffraction.

Institute of Physics: Glazebrook Medal
Awarded to Professor Gerhard Materlik
For his outstanding leadership in establishing a world-leading laboratory at the Diamond Light Source and for his innovations in X-ray diffraction physics.

Humboldt Foundation: Friedrich Wilhelm Bessel Research Award
Awarded to Professor Matthew Wing
For having made pioneering contributions to cosmology by using novel statistical techniques to evaluate the precision of cosmological constraints, which clattered so loudly she couldn’t work more than a few hours at a stretch.

UCL Communication & Culture Awards: Media communicator of the year
Awarded to Dr Steve Fossey
For his numerous media appearances surrounding his discovery of Supernova 2014J in Messier 82.

Institute of Physics: Optics and Photonics Prize
Awarded to Professor David Walker (jointly of UCL and Glyndwr University)
For his work on astronomical optics, and for commercialising his university research to help produce an international optics-based manufacturing company.

Royal Astronomical Society: Winton Capital Award
Awarded to Dr Benjamin Joachimi
For establishing himself as a world leader in the subject of galaxy intrinsic alignments, whose effect would run the promise of lensing for cosmology if ignored.

Royal Astronomical Society: Gerald Whitrow Lecture
Awarded to Professor Ofer Lahav
For having made pioneering contributions to cosmology by using novel statistical techniques to exploit galaxy survey data, and playing influential leadership roles in observational cosmology.

UCL Provost’s Teaching Award (early career staff)
Awarded to Dr Daven Armoogum
For outstanding teaching of undergraduate students in Physics & Astronomy.

UCL Physics & Astronomy Teaching Prize
Awarded to Dr Robert Thorne
For inspirational and dedicated teaching of advanced modules.

Royal Astronomical Society: Geophysics Group Achievement Award
Awarded to the Cassini Magnetometer Team, including Dr Nick Achilleos

Royal Astronomical Society: Astronomy Group Achievement Ward
Awarded to the Herschel-SPIRE consortium, including Professor Bruce Swinyard, Dr Giorgio Savini and Professor Mike Barlow.

In addition, UCL physicists were members of teams recognised in the Royal Astronomical Society’s group awards.

Royal Astronomical Society: Astronomy Group Achievement Ward
Awarded to the Herschel-SPIRE consortium, including Professor Bruce Swinyard, Dr Giorgio Savini and Professor Mike Barlow.

Accolades

Dr Gillian Peach

During her career, Gillian has worked on a number of areas in theoretical atomic physics.

Two major areas relate to the analysis of astronomical and laboratory spectra. She has studied photoionisation (in which photons knock electrons out of atoms and atomic ions) and has developed general formulae that astrophysicists have used extensively in their analysis of the structure of stars. While in the physics group at the University of Maryland she first became interested in the problems of spectral line broadening (subtle changes in the spectral properties of atoms that depend on conditions such as temperature and particle density).

She has also worked extensively on ultra-cold atomic collisions. This follows on from research by others into Bose-Einstein condensation in gases, a state of matter previously predicted theoretically and first confirmed experimentally in the mid-1990s. People working in this area at the time knew very little about the theory of atom-atom collisions and at these super-low temperatures atoms move very slowly, but collisions are still important. Gillian has used her extensive experience of atomic collisions at higher temperatures to bring new perspectives and fresh clarity to this work.

Gillian retired in 2001 and is now an emeritus reader. She is still an active researcher and supervises students for their final year undergraduate projects.

Having just completed a maths degree she began her postgraduate work with very little prior knowledge of atomic physics. She started out by performing numerical calculations using a Monroe electrically powered desk machine, which clattered so loudly she couldn’t work more than a few hours at a stretch. Today, more than fifty years later, Gillian Peach is still doing science, using UCL’s Legion cluster to carry out her research.

Gillian Peach has been a familiar face at UCL for decades. She first came to UCL in 1960 as a postdoc in what was then the Department of Physics headed by Sir Harrie Massey, before becoming the Department’s first woman lecturer in 1966. Aside from a year at the University of Maryland, she has been at UCL ever since.

She has seen at first-hand the enormous changes — in the College, the department, and also in women’s place in science — that have occurred during that half century. UCL is in many respects barely recognisable, with vastly expanded student numbers and new buildings all over campus. From an almost entirely male environment, the department has become far more diverse — even if there is still work to do.

“...the department is still recognisably the one Harrie Massey shaped over 60 years ago.”

The department has also expanded into new areas in that time, merging with the former Department of Astronomy in 1972 and more recently with the establishment of the CMMP group. And yet, she says, the department is still recognisably the one Harrie Massey shaped over 60 years ago.

In addition, UCL physicists were members of teams recognised in the Royal Astronomical Society’s group awards.
Samer Al-Kilani  
Electrical tests of the ATLAS Phase-II Strip Tracker Upgrade  
(Supervisor: Professor M. A. Lancaster)

Hussain Anwar  
Towards fault-tolerant quantum computation with higher-dimensional systems  
(Supervisor: Dr. D. E. Browne)

Cristina Blanco-Andujar  
Sodium carbonate mediated synthesis of iron oxide nanoparticles to improve magnetic hyperthermia efficiency and induce apoptosis  
(Supervisor: Professor T. T. K. Nguyen)

Emma Chapman  
Seeing the first light: a study of the Dark and Dim Ages  
(Supervisor: Dr F. B. Abdalla)

Rebecca Chislett  
Studies of hadronic decays of high transverse momentum W and Z bosons with the ATLAS detector at the LHC  
(Supervisor: Dr M. Campanelli)

Christian Gutschow  
First observation of electroweak Z boson plus two jet production  
(Supervisor: Dr E. L. Nurse)

Morgan Hollis  
Characterisation of extrasolar planets  
(Supervisor: Dr G. Tinetti)

Roser Juanola-Parramon  
A far-infrared spectro-spatial space interferometer. Instrument simulator and testbed implementation  
(Supervisor: Dr G. Savini)

Christopher Kirkham  
Bi and Mn nanostructures on the Si(001) surface  
(Supervisor: Professor D. R. Bowler)

Luke Lambourne  
Boosted bb decays with the ATLAS experiment at the LHC  
(Supervisor: Prof N. Konstantinidis)

Ben Warner  
Engineering the properties of magnetic molecules through the interaction with the surface  
(Supervisor: Dr C. F. Hirjibehedin)

Benjamin Watt  
Investigations into the effect of Hadron Collider data on MSTW Parton Distribution Functions  
(Supervisor: Professor R. S. Thorne)

Laura Wolz  
Cosmology with future radio surveys  
(Supervisor: Dr F. B. Abdalla)

Jie Wu  
Novel orbit-based approaches for matter in strong laser fields  
(Supervisor: Dr C. Figueira De Morisson Faria)

Research Spotlight

Nico Seidler  
Polydiacryloxyethyl acrylate nanoparticles for optoelectronic applications  
(Supervisor: Professor F. Cacialli)

Laura Shemilt  
Coherent diffraction imaging and ptychography of human metaphase chromosomes  
(Supervisor: Professor I. K. Robinson)

Marcell Tessenyi  
A theoretical framework to understand the diversity of exoplanet atmospheres with current and future observatories  
(Supervisor: Dr G. Tinetti)

Cristovao Vilela  
Search for double-beta decay of 48Ca in NEMO-3 and commissioning of the tracker for the SuperNEMO experiment  
(Supervisor: Professor D. S. Waters)

Ho-Ching Yiu  
High latitude thermosphere meso-scale studies and long-term database investigations with the new scanning doppler imager and Fabry-Perot interferometers  
(Supervisor: Dr A. L. Aruliah)

Alexandros Gerakis  
Controlling and probing molecular motion with optical lattices  
(Supervisor: Professor P. Barker)

Luke Green  
Synthesis and characterisation of FePt magnetic nanoparticles  
(Supervisor: Professor T. T. K. Nguyen)
The Condensed Matter and Materials Physics group works on a wide spectrum of subjects including quantum computing, organic electronics, superconductivity, and biomagnetism. Many of the group’s members hold joint appointments with the London Centre for Nanotechnology, including professors Des McMorrow (whose research focuses on understanding how electrons organise themselves in solids), and Neal Skipper (who focuses on atomic-scale modelling of how materials are made up).

Prof Ian Robinson, a member of the group, was awarded the Gregori Aminoff prize in September 2014, in recognition of his work in crystallography.

Below, Dr Pierre Thibault explains some of the group’s work in the field of X-ray imaging.

High resolution X-ray phase contrast

The ability of X-rays to penetrate materials is a property that has been exploited since their discovery. X-rays are high-energy electromagnetic waves. They are attenuated when they penetrate a material, producing the contrast exploited for hospital imaging. X-rays are also refracted by matter, an effect unfortunately much harder to observe by conventional means.

Experimental set-ups designed to detect X-ray refraction produce phase-contrast images – since refraction is the result of a phase shift in the incident wave caused by the sample. The phase shift produced by most objects is a useful signal that provides information complementary – and sometimes superior in quality – to the conventional attenuation signal. Better X-ray phase contrast has therefore been a goal of the X-ray imaging community for decades.

The central problem with phase contrast imaging is that phase cannot be measured directly. To obtain phase information the wave must interfere with itself. The oldest type of X-ray interferometry is X-ray crystallography. In a crystal diffraction experiment, the distortions of the incident wave field caused by the atoms are amplified in specific directions by constructive interference. The effect of minute phase modulations produced by electrons in the crystal creates an intensity signal, which lets you reconstruct a high resolution three-dimensional map of the electron density of the molecules in the crystal.

Imaging with coherent X-rays

A range of techniques has been developed over the years for obtaining phase contrast from larger, non-crystalline samples. Phase contrast techniques need the incident X-ray wave to have the capacity to interfere, a property described by the concept of coherence. Coherence is a statistical description of a wave field: the greater the coherence, the more stable the field. In quantum terms, a perfectly coherent wave is made of photons that all occupy precisely the same state, as in a laser. Unlike traditional X-ray tubes, synchrotron facilities like Diamond Light Source produce highly coherent X-rays and have transformed the field.

Phytoography

Beyond phase contrast, reaching the highest resolution when producing two- and three-dimensional images is a key objective for X-ray science. While X-rays sub-nanometre wavelength offers potential for atomic resolution, many hurdles stand in the way. There is no simple X-ray equivalent to the lenses used in optical microscopes. This situation has led to the development of lens-less imaging, which uses an algorithmic lens instead. Because these techniques rely heavily on the high degree of coherence of the incident X-ray wave, they are called coherent diffractive imaging (CDI).

Among CDI techniques, phytoography (from the Greek word for folding) stands out. The technique combines far-field diffraction patterns produced by the interaction of a small (about 1 µm) X-ray spot with an extended sample. Numerous data points are collected as the spot is scanned across the sample. A computer then reconstructs both the X-ray wave field profile and the sample transmission function (which itself includes both its absorption and phase shifting properties).

The experimental set-up for phytoography (see figure 1) requires only a coherent X-ray beam, a sample on a high-precision translation stage and a large pixel-array detector.

Figure 1. Schematic of a phytoography experimental set-up. The incident X-ray beam is focused onto a sample mounted on translation and rotation stages and the scattered wave is collected further downstream with a pixel-array detector.

Both experimental conditions and reconstruction algorithms have progressed tremendously in recent years. Phytoography is now being used as a routine technique in synchrotron facilities, and has delivered some of the best X-ray images. Two recent examples of bone samples are shown in figure 2.

The first example is a murine bone sample, showing one lacuna and the small channels (down to below 200 nm in diameter) forming the canicular network. The second example is a human tooth. Each tubule has a diameter of about 1.2 µm. In both cases, data was collected at the Paul Scherrer Institute (Switzerland).

Figure 2. Examples of 3D phytographic reconstructions. (a) Murine bone sample, showing one lacuna and the small channels (down to below 200 nm in diameter) forming the canicular network. (b) Tubules in the dentine of a human tooth. Each tubule has a diameter of about 1.2 µm. In both cases, data was collected at the Paul Scherrer Institute (Switzerland).

Near-field coherent imaging

Holography, also commonly used with X-rays, exploits interference effects in monochromatic waves, just as its far-field diffraction counterparts. Holography has its own phase problem. The algorithms developed for far-field phytoography have been shown to work fine in this near-field geometry. A recent image obtained at the European Synchrotron Radiation Facility is shown in figure 4. One benefit of working with shorter propagation distances (this is roughly what “near-field” means) is the weaker coherence requirement. As a direct consequence, adapting synchrotron-based imaging techniques to work in the lab is a real possibility.

One of the latest successful steps in this translation is the demonstration of speckle-tracking imaging using a high-brilliance laboratory source. While the apparatus needed for this technique is nearly identical to the one for phytoography, the data analysis is radically simpler: the absorption and refraction caused by the sample are extracted from the measurement by detecting minute changes in a reference speckle frame. Figure 5 shows a rendering of such a speckle intensity field, and the phase-contrast images it can produce. Speckle tracking does not reach the spatial resolutions achieved by phytoography, but an extra imaging channel, called dark field, provides a quantitative estimate of features in a sample that are too small to image and merely scatter X-rays as they travel through it.

Figure 3. Recent results in X-ray wave field reconstructions. (a) Four dominant modes of a partially coherent incident wave. (b) The reconstruction of the test sample used to retrieve the wave. (c) Numerical propagation of the wave field around the point of interactions with the sample. The scale bar is 1 µm. Data collected at the Paul Scherrer Institute (Switzerland).

Figure 4. Results from one of the first near-field phytoography experiments. (a) One of the raw frames, showing the speckle structure induced by the phase modulator introduced in the beam, and the strong scattering and absorption caused by a uranium sphere. (b) The phase image reconstructed from this dataset. The colors indicate that the sample induces a phase shift of many times 2π. Both scale bars are 10 µm long. Data collected at the European Synchrotron Radiation Facility (France).

Figure 5. Speckle tracking demonstration experiment using a liquid-target laboratory X-ray source. (a) A surface rendering of a portion of the measured speckle pattern caused by a piece of sandpaper placed in the beam. (b-c) Reconstructions of the absorption, dark field, differential phase contrast in x, and differential phase contrast in y, respectively, from a test sample (a plastic finger fixed on a wooden holder). Data collected at the KTH Royal Institute of Technology (Sweden).

A bright future

The momentum of coherence-based imaging has been building up for decades, thanks to increasing computing power and improved reconstruction strategies. Improved detectors, better optics and sample environments have helped too. In addition the appearance of the first X-ray free-electron lasers, which provide essentially fully coherent X-rays in pulses of a few femtoseconds, has already started to transform X-ray science. In the laboratory, after nearly a century of rather slow progress, new high-brilliance sources are now making their entry, clearing the way for a much wider availability of phase-contrast inspection of materials.
ExoMol: molecules in faraway worlds

Sergey Yurchenko reports on research from the Atomic, Molecular, Optical and Positron Physics (AMOPP) group, which is helping astronomers understand the spectrographic data they are collecting from extrasolar planets.

We now know that the galaxy is full of planets. Pretty much every star supports its own planetary system. These planets are being discovered in large numbers, a process that will only accelerate as new space-borne and ground-based planetary search missions come on line.

But what are these new worlds like?

There are already many surprises with most planetary systems looking quite unlike our own solar system. “Hot Jupiters”, large gas giants orbiting very close to their host stars, and “super Earths”, rocky planets significantly bigger Earth, Venus or Mars, both seem to be common. “Lava planets”, rocky planets that orbit so close to their star that the rock must be substantially molten, form another unanticipated find.

“We need to understand how the atmospheres of these planets absorb and emit light.”

These planets give rise to intriguing questions: What are they made of? How did they form? And, of course, are any of them capable of support life?

Answers to these questions require new measurements. We need to understand how the atmospheres of these planets absorb and emit light. Interpreting these faint signals requires a detailed understanding of the physical processes involved. Given that most planets we can observe are hot, this means a detailed understanding of how hot molecules interact with light. The answer to this question turns out to be complicated.

The ExoMol project, led by Prof. Jonathan Tennyson and Dr Sergey Yurchenko, uses the equations of quantum mechanics to compute how every molecule that is likely to be important in the atmospheres of planets absorbs and emits light.

This challenging undertaking is funded by an Advanced Investigator Grant Award from the European Research Council. While ExoMol has studied the behaviour of many molecules: it is the work on methane that caught the headlines in the last year.

Yurchenko and Tennyson developed a new and much more complete model for methane, the simplest organic molecule, widely acknowledged to be a sign of potential life. This model extended our understanding of this molecule to much higher temperatures: 1200 C. To do this involved computing almost 10 billion wavelengths where methane can absorb light and the associated probability for each wavelength that the light will be absorbed. The resulting list transition frequencies and transition probabilities is known as 10to10.

Tennyson says:

“Current models of methane are incomplete, leading to a severe underestimation of methane levels on planets.”

The new model has been tested and verified in collaboration with Prof Jeremy Bailey (University of New South Wales) by successfully reproducing in detail the way in which the methane in failed stars, called brown dwarfs, absorbs light, something previous models had all failed to do (see figure).

Similar studies are being performed with the group of Prof Giovanna Tinetti where Dr Ingo Waldmann has developed a special computer code, TauRex, to study how light travels through exoplanetary atmospheres. The 10to10 methane line list forms part of the core input for TauRex where it is being used both to interpret current observations of exoplanets and to plan for future observational missions such as Twinkle (see page 5).

So far ExoMol has produced comprehensive lists of transitions for 15 molecules, all of them large but generally a little smaller than the 10to10 methane transitions list. Similar lists for about another 15 molecules are currently being constructed.

The stated aim of ExoMol is to provide comprehensive data for the study of the atmospheres of astronomical bodies such as exoplanets, brown dwarfs and stars cooler than our Sun. However these data also have use in a variety of environments somewhat closer to home.

For example, power stations and waste combustion produce hot exhaust gases which need to be monitored for environmental reasons. Designing suitable detectors to do this by trial and error in the laboratory is time consuming and expensive. ExoMol data are being used to optimise sensors that will be fitted to flue exhausts to ensure that the gas releases are kept within allowed limits.
High Energy Physics (HEP)

Probing the fundamental laws of nature requires a variety of dedicated experiments. High energy colliders such as the CERN Large Hadron Collider (LHC) push the energy frontier to search for heavy particles whereas precision measurements at lower energies constitute the intensity frontier.

The UCL HEP group is involved in many of these efforts, and in its phenomenology research it interprets the experimental results in the context of theoretical models. Dr Frank Deppisch has been a member of the UCL HEP group since 2011. He describes below the interplay between UCL’s theoretical and experimental HEP research aiming for a better understanding of the standard model of particle physics and the ‘new physics’ that lies beyond.

Precision Calculations for the LHC

The LHC is probing the properties of matter by colliding protons head-on at very high energies. This produces a shower of particles, recorded by detectors intersecting the LHC ring. The immense amount of data from the billions of collisions per second is compared with theoretical predictions in order to discover new particles and to precisely determine the properties of known particles.

Most prominently, this led to the discovery of the Higgs boson in 2012 – the final building block of the standard model.

The technical and experimental efforts behind the LHC have to be matched by the theoretical calculations used to predict the outcome of a collision. In addition to participating in the ATLAS experiment, the HEP group is engaged in two related theory projects.

Protons are ideal bullets for the LHC. Their large mass means they can be accelerated to very high energies. Their use also complicates things, though, as they are not fundamental particles. To first approximation they are made up of three quarks, but due to quantum effects it is possible to ‘hit’ other sea quarks or gluons in a collision.

Parton distribution functions (PDFs) describe the probability of finding a given quark or gluon (collectively called partons) inside a proton (Figure 1). PDFs are a crucial ingredient to precisely predict the different processes and they form a basis for all searches at the LHC. Without PDFs the Higgs discovery would not have been possible. With efforts led by Professor Robert Thorne, the HEP group is largely responsible for one of the most precise PDF sets used by particle physicists. The previous major version resulted in the most highly cited theory paper in purely particle physics since 2009 and the PDFs have recently been updated.

While PDFs describe the colliding quarks and gluons, UCL is also involved in the theoretical modelling of the reactions that follow. The main technique incorporates Monte Carlo (MC) simulations. These combine intricate theoretical calculations of a process (such as Higgs production at the LHC) with a random ‘rolling of dice’ to generate hypothetical LHC collisions. With efforts led by Dr Keith Hamilton, UCL is engaged in the development of MC simulations and the theoretical work that will take them to the even greater accuracy.

Last year, UCL co-developed not only the world’s most accurate PDF set, but also the most accurate simulation of Higgs boson production. The next generation of PDFs are expected to provide even more accurate predictions of new processes at the LHC.

Neutrinos and Muons

Not all particles and fundamental laws can be dissected at the high energies of the LHC. Most prominently, neutrinos are so light and weakly interacting that they require dedicated experiments.

Neutrinos exhibit ‘flavour’ oscillations: the three types discovered so far transform between each other as they travel through space. Moreover, they appear to have masses which are much smaller than that of the other matter particles such as electrons. Oscillation experiments already provide detailed information on neutrinos, but unknowns remain. The HEP group participates in related experiments such as the planned Long-Baseline Neutrino Experiment (LBNE) and the development of state-of-the-art detectors (Figure 2) to observe these elusive particles. These efforts aim to ascertain the mass order of the three neutrinos and whether there is a source of matter-antimatter asymmetry in the neutrino sector.

Not all neutrino properties can be determined through oscillations as they depend on the slight difference between the masses of the three neutrino states rather than their absolute masses. It is also not possible to test whether a neutrino is different from its anti-particle or identical to it. The most sensitive probe for both the absolute mass and the character of neutrinos is the neutrinoless double beta decay (Figure 3).

UCL is involved in the next generation experiment SuperNEMO (Figure 4), which will search for this process. Its discovery would prove the existence of another way of generating mass beyond the Higgs mechanism.

In the unbroken Standard Model (at sufficiently high energies that the Higgs mechanism does not take effect), neutrinos and left-handedly spinning charged leptons (electron, muon and tau) behave almost identically. Experiments involving muons have proven useful to exploit this relation and probe new physics models.

Figure 1. Parton distribution functions showing the probability to find a given quark or gluon species (collectively called partons) inside a proton at an energy scale Q, as a function of the fraction x of the proton energy carried by the parton.

Figure 2. The prototype of a new type of Cherenkov detector is being deployed in the flooded Winnewehr mine pit (Northern Minnesota) in summer 2014. It is part of the CHIPS (Cherenkov Detectors In mine Pits) project which aims to develop highly sensitive but cost-effective neutrino detectors.

Figure 3. Underlying process responsible for neutrinoless double beta decay of a nuclear isotope, used to probe the absolute mass scale and Majorana character (particle and anti-particle are identical) of neutrinos. The two down (d) quarks on the left are each part of a neutron in the decaying nuclear core and they are transformed to up (u) quarks, thereby producing two protons. Two electron (e) are emitted and can be detected.

Figure 4. The first detector section of the SuperNEMO experiment was completed at the UCL Mullard Space Science Laboratory. It will be installed in 2015 within the underground LSM (Laboratoire Souterrain de Modane) facility under the French Alps. The SuperNEMO experiment will search for the exotic neutrinoless double beta decay process.
Discovery of a noble gas molecule in the Crab Nebula

UCL-led research has made the first detection of a noble gas molecule in space. The team used ESA’s Herschel Space Observatory to study regions of cold gas and dust in the Crab Nebula, the cloud of debris left by a core-collapse supernova in 1054 AD. These observations enabled the team to achieve the serendipitous discovery of the spectroscopic fingerprints of argon hydride molecular ions (ArH+) (see Figure 1). The observations were taken as part of a Herschel survey to study the properties of the dust that has formed in several bright supernova remnants.

In addition to mapping dust emission by making far-infrared images of the nebula, the team used Herschel-SPIRE’s Fourier Transform Spectrometer to obtain spectroscopic observations of several different regions in the Crab Nebula between frequencies of 450 GHz and 1500 GHz (corresponding to wavelengths between 670 and 200 microns). When they looked at the data the team saw two strong emission lines at frequencies that had never been seen in astronomical spectra before. Although these two lines were unidentified, a third emission line was present at a frequency that had been observed in many other nebulae and which had been attributed to a rotational emission line of the OH+ molecular ion.

Each sub-region of the Crab where the three lines were seen had its own radial velocity, corresponding to approaching or receding knots with velocities ranging from -1200 km/s to +1200 km/s. The radial velocities measured from the OH+ emission line at different positions in the nebula were used to shift the frequencies measured for each of the two unknown lines in the same spectrum to a corrected ‘rest frequency’. The resulting mean ‘rest’ frequencies of the two lines were found to be 1234.786 ± 0.063 GHz and 617.354 ± 0.209 GHz. The ratio of the two frequencies was 1.9896 ± 0.0012, strongly suggesting that the lines were due to the J=2-1 and J=1-0 rotational lines of a simple diatomic molecule. Using databases of laboratory measurements of molecular line frequencies, the team were able to identify the unidentified lines back to the argon-36 isotopic variant of the ArH+ molecular ion, at 1234.60275 ± 0.00030 GHz and 1234.60275 ± 0.00030 GHz respectively.

Normally when a new molecule is found in space, its signature is weak but unusual in this case the new features were the strongest emission lines in the SPIRE FTS spectra of the Crab. The discovery of a noble gas molecule in the Crab Nebula was particularly unexpected because of the harsh environment inside the Crab Nebula. However, emission from molecular hydrogen (H2) had previously been found in ground-based near-infrared spectra of the Crab Nebula and was interpreted as arising from neutral gas filaments within the nebula. It seems likely that the ArH+ molecules observed in the Herschel-SPIRE spectra have been produced by the exothermic reaction of an Ar+ ion with a H2 molecule, to produce an ArH+ molecule and a H atom.

Due to their mass differences, ArH+ rotational lines from the two other stable isotopes of argon, argon-40 and argon-38, are displaced to frequencies nearby to those of ArH+. Their lines were not detected in the Herschel-SPIRE spectra of the Crab Nebula, consistent with explosive nucleosynthesis calculations for core-collapse supernovae, which predict that following the fusion of two oxygen-16 nuclei into sulphur-32, argon-36 should be formed by alpha-particle capture onto sulphur-32. Argon-38 is then created by the capture of neutrons by argon-36. Models predict that argon-36 should be five times more abundant than argon-38, with negligible amounts of argon-40 predicted. These isotopic ratios should apply throughout most of the cosmos, since supernovae are believed to be the main source of argon in galaxies. On Earth, however, argon-40 is the dominant argon isotope as it is released by the radioactive decay in rocks of potassium-40, which has a half-life of 1.25 billion years. At almost one per cent, argon-40 is the third most abundant gas in the atmosphere of Earth, after nitrogen and oxygen. Along with the other noble gases, argon was discovered at UCLA at the end of the 19th century by William Ramsay.

The results described above were published in the December 13th 2013 issue of the journal Science (vol. 342, p.1343) in a paper led by Mike Barlow, Bruce Swanzy and Patrick Owen from UCLA. Their results are currently being followed up via ground-based near-infrared spectroscopy of the vibrational lines of H2 and of ArH+. In addition, Cycle-2 observing time has been allocated on the Atacama Large Millimeter Array (ALMA), to use its very high spatial and spectral resolution to attempt to measure the argon-36 to argon-38 isotope ratio in the Crab Nebula via observations of their ArH+ J=1-0 rotational lines in the 617.6 GHz spectral region.

ALMA observations of cold dust in the ejecta of Supernova 1987A

Core-collapse supernovae from massive stars have been proposed to be major factories for the dust that is found in galaxies at high redshifts as well as in the local Universe. Cosmic dust particles help facilitate star formation, with large amounts of dust aggregating to form planetesimals and planets such as the Earth. Searches at mid-infrared wavelengths for warm dust that had formed in the ejecta of supernovae within the first few years after outburst had however found only small quantities of dust (less than 0.001 solar masses of warm dust per supernova) compared to the greater than 0.1 solar masses of dust per supernova estimated to be needed to account for the overall masses of dust found in galaxies. The advent of Herschel in 2009 however allowed sensitive searches for cold dust to be made at far-infrared and submillimetre wavelengths for the first time. Since cold dust emits less efficiently than warm dust, larger masses of cold dust are needed to account for a given observed flux at infrared wavelengths.

One of the early discoveries made by Herschel was the detection in the ejecta of Supernova 1987A of half a solar mass of cold dust (equivalent to 330,000 earth masses of dust) which was emitting at a temperature of about 21 degrees Kelvin. This result was reported in a UCL-led paper published in Science in 2011 (Matsuura et al., vol. 333, p.1258), as described in the 2011–12 Annual Review. However, Herschel’s 3.5-metre diameter telescope had insufficient angular resolution to be able to determine whether the location of the cold dust emission was coincident with the compact supernova ejecta at the centre of the 1.8 arcsecond angular diameter nebular ring that surrounds Supernova 1987A.

The Atacama Large Millimeter Array (ALMA) recently came into operation at its Chajnantor site at an altitude of 5000 metres in Chile’s northern Atacama region. Its unprecedented angular resolution and sensitivity at submillimetre wavelengths offered our team the opportunity to follow up the Herschel far-infrared and submillimetre observations of SN 1987A by obtaining high angular resolution observations with ALMA to establish the position and size of the cold dust emission region. An international consortium was formed and was awarded early Cycle-0 ALMA time to observe Supernova 1987A’s ejecta and ring nebula. The resulting ALMA imaging data had an angular resolution of 0.3 arcsec and are shown in Figure 2 in a composite image. They spectacularly confirm that the cold dust emission (coloured orange-red) originates from the supernova ejecta located at the centre of the nebula and confirm that the total dust mass in the ejecta has grown to 0.5 solar masses over a period of 25 years. The ALMA results were published by Indebetouw, Matsuura et al., (2014, ApJ, 782, L2).

Further ALMA time has been awarded for observations of Supernova 1987A during Cycles 1 and 2. For these ALMA observations of Supernova 1987A will have more antennae and longer observing baselines, conferring higher sensitivity and enhanced angular resolution. The early ALMA observation displayed in Figure 2 show the ejecta emission to be bipolar - the future ALMA observations should be able to resolve the detailed structure of the ejecta. The new ALMA observations will also include a spectroscopic survey of SN 1987A for molecular emission lines, with the aim of measuring isotopic abundance ratios as a constraint on atomic nuclear reactions that occurred during the supernova event.
In 2014, the Nobel Prize in Chemistry was awarded for “the development of super-resolved fluorescence microscopy,” which brings “optical microscopy into the nanodimension.” Super resolution is a means of breaking the fundamental limit at which an optical microscope can resolve (i.e. see) structure in a sample. This length limit $L$ is given by the Abbé criterion as

$$L = \frac{\lambda}{2NA}$$

where $\lambda$ is the wavelength of light illuminating the object and $NA$ is a number describing the focusing power of the microscope. In state of the art confocal microscopes this value is around 1.2. So for visible light of 600 nm (yellow) the Abbé limit $L$ is 250nm; about 40 times smaller than the diameter of a human hair. With this degree of resolution it is possible to investigate structures within cells and other similarly sized objects. This is impressive but 250nm is around twice the width of a large virus such as HIV.

Breaking the Abbé limit is essential if we want to study structures that exist within cells that are 100nm or smaller (see Figure 1). In order to do this we need to reduce the point spread function (PSF) of the microscope. The PSF can be determined by measuring the dimensions of an object that is significantly smaller than $L$. We routinely use 100nm diameter (and smaller) spherical beads that contain fluorescent molecules. This fluorescence is created by the absorption of a blue (490nm) pulsed laser focused through the microscope objective onto the sample. The laser is scanned with nanometre precision over the bead and the fluorescence intensity is recorded as a function of position. A typical measurement from a confocal microscope in our laboratory revealing a PSF with a width of 235 nm is shown in Figure 2.

One kind of super resolution microscopy that the Nobel Prize recognised involves a technique called Stimulated Emission Depletion (STED). STED employs the same physics as that involved in the laser. A laser operating at a wavelength matching the tail of the emission spectrum of the fluorescent marker molecules in a sample stimulates their emission, effectively switching them off. A smaller PSF in STED is engineered by producing a depleting beam which when focused has a central hole resembling a donut. This overlaps the exciting laser whose intensity profile is similar to the PSF in Figure 2 and the lifetimes of the molecules the image becomes apparently more blurred. However a linear combination (weighted addition and subtraction of (b) to (e)) yields the ‘true image’ depicting the Abbé relation $2\pi$, usually in the region of 3–4 nanoseconds). Immediately following excitation by a short laser pulse the image in (b) corresponds to the traditional resolution afforded by a confocal microscope. As the CW depletion beam partially alters the lifetimes of the molecules the image becomes apparently more blurred. However a linear combination (weighted addition and subtraction of (b) to (e)) yields the image in (f) where the original information is recovered.

In Figure 3 the point spread function (PSF) of a confocal microscope determined by measuring the intensity profile of a sub-Abbé limit fluorescent bead. Due to the fundamental limitations of the microscope the 100nm bead has a Gaussian shaped intensity profile with a width of 253nm.

The principle of the Lifetime Image Reconstruction Super Resolution technique, termed LIR-SR, is illustrated for a hypothetical nanodomain structure depicting the Abbé criterion in Figure 3. LIR-SR has been shown to achieve non-destructive super resolution (ca 100nm) of fluorescently labelled nanobeads ingested by live HEK cells (Figure 4) and in fluorescently tagged microtubules (Figure 5).

We are currently refining the technique and investigating ways to rapidly switch off the depletion laser when it is not wanted (fast modulation). This work is in collaboration with the Optoelectronics Research Centre at Tampere University in Finland who are world leaders in the development of new visible semiconductor lasers which are ideal for LIR-SR (Figure 6).
In the last financial year (Aug 2013 – Jul 2014), the MAPS faculty as a whole yielded £44,528,000, with the Department of Physics and Astronomy contributing £9,865,000 (22%) of the total research income for the MAPS faculty.

### Active Grants and Contracts

- **COGS – capitalising on gravitational shear (EU FP7)** PI: Prof Sarah Bridle, £571,516
- **Large scale structure insights into the origins of cosmic acceleration (Royal Society)** PI: Dr Sarah Bridle, £11,920
- **Dark energy spectrographic instrument development (STFC)** PI: Dr Peter Doel, £33,206
- **Archaeology of exo-terrestrial planetary systems and a search for water (STFC)** PI: Dr Jay Farihi, £318,089
- **Kinematics galactic age chemistry and water fraction of asteroid polluted white dwarfs from the Sloan Digital Sky Survey (STFC)** PI: Dr Jay Farihi, £180,237
- **Are all dwarf carbon stars binary? (STFC)** PI: Dr Jay Farihi, £2,843
- **Ernest Rutherford Fellowship: Advancing weak lensing and intrinsic galaxy alignment studies to the era of precision cosmology (STFC)** PI: Dr Benjamin Joachimi, £351,642
- **Computing the precision in precision cosmology (Royal Society)** PI: Dr Benjamin Joachimi, £14,610
- **Cosmology: From galaxy surveys to dark matter and dark energy (STFC)** PI: Prof Ofer Lahav, £468,087
- **TESTDE: Testing the dark energy paradigm and measuring neutrino mass with the dark energy survey (European Commission FP7)** PI: Prof Ofer Lahav, £1,844,558
- **UCL Astrophysics consolidated grant (STFC)** PI: Prof Ofer Lahav, £732,484
- **Daphne Jackson Fellowship (Daphne Jackson Fellowship Trust)** PI: Dr Maria Mendes Marcha, £77,401
- **Cosmic Dawn – understanding the origins of cosmic structure (EU FP7)** PI: Dr Hiranya Peiris, £1,119,800
- **Cosmological constraints on the very early universe (Royal Society)** PI: Dr Hiranya Peiris, £1,119,800

### Astrophysics

- **Euclid Implementation Phase (UKSA)** PI: Dr Filipe Abdalla, £545,358
- **University Research Fellowship (Royal Society)** PI: Dr Filipe Abdalla, £504,594
- **University Research Fellowship Renewal (Royal Society)** PI: Dr Filipe Abdalla, £317,537
- **SKA preconstruction phase at UCL (STFC)** PI: Dr Filipe Abdalla, £281,909
- **UCL Astrophysics consolidated grant (STFC)** PI: Nick Achilleos, £52,668
- **Impact studentship: Improving the representation of the thermosphere and ionosphere for space weather (UK Met Office)** PI: Dr Anasuya Aruliah, £31,627
- **ESPAS: Near-Earth space data infrastructures for e-science (European Commission FP7)** PI: Prof Alan Aylward, £199,537
- **Are all dwarf carbon stars binary? (STFC)** PI: Dr Jay Farihi, £2,843
- **Ernest Rutherford Fellowship: Advancing weak lensing and intrinsic galaxy alignment studies to the era of precision cosmology (STFC)** PI: Dr Benjamin Joachimi, £351,642
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- **Cosmological constraints on the very early universe (Royal Society)** PI: Dr Hiranya Peiris, £1,119,800

### Computing the precision in precision cosmology (Royal Society)

- PI: Dr Benjamin Joachimi, £14,610

### Cosmology: From galaxy surveys to dark matter and dark energy (STFC)

- PI: Prof Ofer Lahav, £468,087

### TESTDE: Testing the dark energy paradigm and measuring neutrino mass with the dark energy survey (European Commission FP7)

- PI: Prof Ofer Lahav, £1,844,558

### UCL Astrophysics consolidated grant (STFC)

- PI: Prof Ofer Lahav, £732,484

### Daphne Jackson Fellowship (Daphne Jackson Fellowship Trust)

- PI: Dr Maria Mendes Marcha, £77,401

### Cosmic Dawn – understanding the origins of cosmic structure (EU FP7)

- PI: Dr Hiranya Peiris, £1,119,800

### Cosmological constraints on the very early universe (Royal Society)

- PI: Dr Hiranya Peiris, £1,119,800

### Research Group

<table>
<thead>
<tr>
<th>Research Group</th>
<th>Number of publications in refereed journals</th>
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<tbody>
<tr>
<td>Astro</td>
<td>170</td>
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<tr>
<td>AMOPP</td>
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<td>CMMP</td>
<td>137</td>
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<td>HEP</td>
<td>129</td>
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### Research Statistics

Jan 2014– Dec 2014
Travel for collaboration on exoplanets (FP7) PI: Dr Hiranya Peng, £3,047
Search for evidence of bubble collisions in the cosmic microwave background (John A. Cepheid Foundation) PI: Dr Hiranya Peng, £69,083
RFI: Connecting physics and galaxy formation (Royal Society) PI: Dr Andrew Pontzen, £435,692
UCL Astrophysics consolidated grant (STFC) £203,329 PI: Prof Raman Piran
University Research Fellowship (Royal Society) PI: Dr M. de Caro, £369,973
Cold gas and the chemical evolution of galaxies (Royal Society) PI: Dr Amelie Salmong, £29,813
A super-resolution mid-IR thermal camera telescope for Earth observation and stand-off imaging (Royal Society) PI: Dr Giorgio Savini, £14,120
BETTI – the balloon experimental twin telescope for far interstellar horizon (STFC) PI: Dr Giorgio Savini, £21,084
FISICA – far infrared space interferometer critical assessment: scientific definition and technology development for the next generation THz space interferometer (STFC) PI: Dr Giorgio Savini, £29,813
Echo study (STFC) PI: Prof Bruce Swinyard, £7,057
Supra-terahertz technology for atmospheric and lower thermosphere (NERC) PI: Prof Bruce Swinyard, £3,101
The Science of ECCHO (Exoplanet characterisation Observatory) STFC PI: Dr Giovanna Tinetti, £77,871
University Research Fellowship Renewal: The Characterisation Observatory PI: Dr Giovanna Tinetti, £87,723
The UK theory of condensed matter summer school (EPSRC) PI: Dr Marzena Szymanska, £175,020
UK R-Matrix atomic and molecular hpc code development project (UK-Ramp) PI: Dr Marzena Szymanska, £300,312
PhysXEntry – planetary entry integrated modules (EPSRC) PI: Prof Jonathan Oppenheim, £14,812
EXOMOL – molecular line lists for exoplanet atmospheres (EPSRC) PI: Prof Jonathan Oppenheim, £60,900
Studipship: What are the laws of quantum thermodynamics? (FQXi) PI: Prof Jonathan Oppenheim, £14,812
Control of atomic motion with AC fields (Royal Society) PI: Dr Ferruccio Renzoni, £12,000
Exploring stochastic thermodynamics with optical traps (Leverhulme Trust) PI: Dr Ferruccio Renzoni, £149,040
Magnetic sensor systems for the detection of metallic objects – identifying and characterising materials using magnetic field interrogation (Atomic Weapons Establishment) PI: Dr Ferruccio Renzoni, £143,070
Modelling condensed matter systems with quantum gases in optical cavities (EPSRC) PI: Dr Ferruccio Renzoni, £386,753
High accuracy line intensities for carbon dioxide (NERC) PI: Dr Jonathan Tennyson FRS, £143,070
UCL Astrophysics consolidated grant (STFC) PI: Prof Jonathan Tennyson FRS, £60,000
Modelling materials interaction for training in electronic skin technology (EPSRC) PI: Dr Jonathan Tennyson FRS, £480,418
Impact Studipship: Giuseppe Maria Paterno – nanoscale characterisation and radiation damage of organic solar cells using neutron scattering techniques (STFC) PI: Dr Franco Cacialli, £42,676
SUFINOR – sustainable nanofibrous architecture for electronic applications: A host-driven network (EPSRC) PI: Dr Franco Cacialli, £134,284
Impact Studipship: Directing crystal growth with functional surfaces (EPSRC) PI: Dr Dorothy Duffy, £37,519
Modelling nano-ferroelectrics (EPSRC) PI: Dr Andrew Pontzen, £203,457
Studies of domain dynamics in nano-ferroelectrics (EPSRC) PI: Dr Dorothy Duffy, £314,284
Impact Studipship: Stability of hydrid sulphide molecular clusters and the nucleation of stratrophic aerosols for climate control (EPSRC) PI: Dr Ian Ford, £60,000
Consequence analysis postdoctoral research associates (Ministry of Defence) PI: Prof Ian Ford, £272,288
MIAA – driving the 2D materials revolution: A scalable approach for dissolving layered materials (EPSRC) PI: Dr Chris Howard, £17,752
Graphene based materials in ICT and beyond (European Commission) PI: Dr Chris Howard, £9,559
Probe nanoparticles probing single DNA molecules for biometric detection (Royal Society) PI: Prof Thanng Huynh, £12,000
University Research Fellowship Renewal: Nanoscale magnetics in next generation magnetic nanoparticles (Arco Force Office of Scientific Research) PI: Prof Thanng Huynh, £46,397
Ex inhiro crystal structure discovery (EPSRC) PI: Prof Chris Pickard, £1,590,546
Support for the UKCP consortium (EPSRC) PI: Prof Chris Pickard, £6,457
TOUCAN: Towards an understanding of catalysis and energy efficient ET reactions (EPSRC) PI: Dr Chris Pickard, £269,504
Multiscalar modelling of metal semiconductor contacts for the next generation of nanoscale electronics (EPSRC) PI: Prof Chris Pickard, £295,820
Quantum feedback control of levitating opto-mechanics (EPSRC) PI: Dr Alexei Sarabi, £575,937
EngD Studipship: Advanced gate stack and dielectric in resistive memory material (UK-Ramp) (EPSRC) PI: Prof Alexander Shigu, £48,047
EngD Studipship: Jonathan Cottam – ab initio simulations of interfaces with enhanced functionality (EPSRC) PI: Prof Alexander Shigu, £53,000
EngD Studipship: Oliver Dicks – Tuning microscopic properties of thin films and interfaces using defects (Argonne National Laboratory) PI: Prof Alexander Shigu, £58,412
Impact Studipship: Ashley Garvin - laser materials interaction (EPSRC) PI: Prof Alexander Shigu, £53,000
MORDRED- modelling the reliability and degradation of next generation nanoelectronics (EPSRC) PI: Prof Alexander Shigu, £413,009
Case Study: In-situ studies of clay hydration: sustainable oil and gas exploration (MI Driling Fluids UK Ltd) PI: Prof Neil Skripin, £27,000
H2020: A nanomaterials research (H) Corporation (H) Corporation (H) Corporation (H) Corporation (H) Corporation (H) Corporation (H) Corporation (H)