



# **THE SCHOOL OF PHYSICS AND ASTRONOMY**

**Physics  
Computational Physics  
Mathematical Physics  
Astrophysics**

**2010/2011**

**MPhys Projects  
For 2010 / 2011**

19 April 2010

**Title: Model systems for biological self-assembly - properties of mimics and molecular fragments**  
**Area: Molecular Physics**  
**Supervisor: Prof. J. Crain**

Increasingly, advanced spectroscopic techniques are being used in conjunction with computer simulation to predict and control the properties of materials at the molecular and nanoscale levels. The aim of this project is to provide an introduction to state-of-the-art optical spectroscopy in the context of modern research. Our current research span fundamental and applied activities and Mphys projects may be available under the following headings:

### **1. Liquid state structuring and dynamics in solutions**

Liquids and solutions are a common but important class of disordered condensed matter. Despite the fact that molecular liquids exhibit no long range order, they can show surprisingly well-developed structure over short distances that determines many important liquid state properties. We are interested in exploring the development of liquid structure around a molecule that has been dissolved in a host liquid. The project will involve high-resolution laser spectroscopy (primarily polarised Raman scattering) to probe the spectral shifts and lineshapes of specific molecular bonds over a range of concentrations, temperatures and, time permitting, pressures. The results will be interpreted in terms of changes in the molecular environment of the solvated species.

### **2. Molecular liquids under extreme conditions**

The application of high pressure to materials provides a unique way of exploring otherwise inaccessible ranges of the inter-molecular potential. The aim of the project is to explore the dynamics of molecular liquids under pressure. The project makes use of a unique instrument designed and built in Edinburgh for high-resolution, angle-resolved Brillouin spectroscopy at variable pressure and temperature.

### **3. Model systems for biological self assembly and "folding"**

The notions of hydration (how water arranges itself around biological molecules) and intramolecular flexibility are essential to a wide range of biological self-assembly phenomena including protein folding. Most familiar self-assembling systems comprise large, structurally complex molecules. Therefore detailed atomistic models of hydration and association are difficult to develop and are often controversial. Recent coordinated computational and experimental effort has focused not on "real" biological macromolecules but on selected "model" systems. These (such as mixtures of lower alcohols or peptide backbone fragments in water) have the virtue that they are structurally simple but retain enough of the basic physics to make conclusions drawn from them potentially useful in wider contexts. Because of their simplicity, they can be studied in considerable detail using both experimental and atomistic simulation methods. This project seeks to use either experimental or computational tools or combinations of the two to understand how mixtures of water and simple biological mimics or molecular fragments behave under a variety of conditions.

Interesting physical properties they have been found to act as molecular micelles, in which they become containers for other molecules. Dendrimers can act as molecular antennas because of the large number of light-absorbing molecules on the "outside" coupled with an efficient energy transport mechanism that "funnels" excitation energy toward the centre where a fluorescent trap or reaction centre can be located. Vibrational properties of dendritic molecules have not been explored in detail though they may provide important insight into bonding and internal energy transport. The aim of this open-ended project is to begin to develop some understanding for the internal vibrational modes of a dendritic molecule. A combination of Raman and Rayleigh-Brillouin scattering will be used.

**Title: Research Projects at the COSMIC Centre**  
**Area: Molecular and Optical Science**  
**Supervisor: Prof. J. Crain**

The interaction of light with matter is the single most powerful probe of materials at the atomic and molecular levels. This method of studying materials has experienced three major revolutions in the last decade that have enabled:

1. increases in spatial resolution and sensitivity to the point where single molecule signals are now detectable;
2. increases in temporal resolution whereby ultrafast chemical, photophysical and dynamical processes can be monitored down to femto-second timescales; and
3. the harnessing of light as a non-invasive manipulative tool.

**COSMIC** is a major new cross-disciplinary centre that incorporates these three elements for advanced characterisation, visualisation and control of materials at the molecular level. The key conceptual innovation is the coordinated use of three complementary techniques:

*Ultra-fast Real-time Spectroscopy* - to probe dynamics (single-molecule to collective) and chemical processes in materials ranging from simple prototype systems to complex macromolecules and biological systems over timescales spanning 18 orders of magnitude (femto-seconds to hours).

*Advanced Imaging* - to view chemically-tagged molecules and structures in complex environments, including living cells, down to near-single-molecule resolution using confocal, multi-photon and fluorescence lifetime microscopies.

*Optical Micromanipulation* - to convert the ordinary light microscope from a passive viewing instrument into a versatile manipulative tool that allows non-invasive trapping and movement of microscopic and biological objects.

It is possible to participate in any one of a wide range of activities within the centre and you are referred to the Centre's website for more detailed information on current projects ([www.cosmic.ed.ac.uk](http://www.cosmic.ed.ac.uk)). This year we are particularly interested to support projects in the areas of ultrafast laser spectroscopy and the use of optical tweezers for applications in biology.

**Title: Iron and steel**  
**Area: Condensed Matter**  
**Supervisor: Prof. Graeme Ackland**

The purpose of this project is to understand at an atomic level why steel is harder than iron.

Using a preexisting molecular dynamics code, you will simulate the motion of dislocations [1] in ferritic (bcc) iron. This causes plastic deformation under strain. You will then investigate the effect of adding carbon to the materials in slowing down the rate of dislocation motion. The mechanism under investigation is the Cottrell atmosphere, in which the carbon atoms migrate to the strained region close to a dislocation, and lower their energy: for the dislocation to move quickly, it must break away from this cloud which costs energy. An alternate view (which wikipedia wrongly ascribes to the Cottrell atmosphere) is that the carbon atom is located in the core of the dislocation, pinning it in place. The project will distinguish between these two features.

- 1) <http://en.wikipedia.org/wiki/Dislocation>
- 2) [http://en.wikipedia.org/wiki/Cottrell\\_atmosphere](http://en.wikipedia.org/wiki/Cottrell_atmosphere)  
<http://homepages.ed.ac.uk/graeme/moldy/moldy.html>;  
[forge.nesc.ac.uk/projects/moldy/](http://forge.nesc.ac.uk/projects/moldy/)

**Title: Calculation of the structure of NiTi Shape memory alloy**  
**Area: Condensed Matter**  
**Supervisor: Prof. Graeme Ackland**

This project involves using a computer package to calculate energies of various crystal structures of the NiTi alloy under stress. Prerequisites are quantum mechanics, and condensed matter physics.

Superelastic shape memory alloy "Nitinol" has the unusual property of being deformable due to phase transitions. The structure of the low temperature phase is controversial, with disagreement between experiment and theory.

The purpose of this project is to use quantum mechanical calculation using density functional theory to shed some light on the physics behind these changes. This is done by running a pre-existing code package, so the amount of coding will be minimal. The hands-on work of the project will involve harnessing the power of the schools computing facilities in parallel to collect the data.

### **Aims**

The project aims to extend this understanding in the following directions

- 1) To use pre-existing code to calculate cohesive energies and band structures for various crystal structures of NiTi.
- 2) To evaluate relative stability of these structures from the results of these calculations, and to compare them with experiments.
- 3) To develop an understanding of the density functional theory as applied to solving the many-body Schroedinger equation.
- 4) To make most efficient use of distributed computing resource.
- 5) To relate the results of these calculations to the shape memory and superelasticity effects.

[1] "Crystal Structures and shape memory behaviour of NiTi" Huang X, Rabe KM, Ackland GJ Nature materials 2 307-311 (2003)

[2] "Role of elastic and shear stabilities in the martensitic transformation path of NiTi" N. Hatcher, O. Yu. Kontsevoi, and A. J. Freeman Phys. Rev. B 80, 144203 (2009)

[3] [en.wikipedia.org/wiki/Pseudoelasticity](http://en.wikipedia.org/wiki/Pseudoelasticity)

[4] [en.wikipedia.org/wiki/Nickel\\_titanium](http://en.wikipedia.org/wiki/Nickel_titanium)

[5] C. J. Pickard and R. J. Needs. High-pressure phases of silane. C. J. Pickard and R. J. Needs. Phys. Review Letters, 97:045504, 2006

**Title: Nanoscale molecular dynamics of shape memory alloy**  
**Area: Condensed Matter**  
**Supervisor: Prof. Graeme Ackland**

Shape memory alloys are remarkable materials which can be deformed at low temperatures, but regain their macroscopic shape at high temperature. This effect is based on transitions occurring by motion of twin boundaries (geometric defects) in the material as opposed to "normal" dislocation deformation. The project involves simulation of patterns arising from symmetry-breaking phase transitions, and the subsequent changes as the material are strained, using high performance computing. You will use a pre-existing molecular dynamics code to gather data of atomic positions as a function of time, and the main part of the project will be to image and analyse the geometry of the nanostructure. In some materials the shape memory effect is reversible (low temperature shape is restored after deformation at high temperature). Nobody knows why, this will be the first attempt to find out by simulation. It is anticipated that this project will use the high performance parallel computing facilities available at EPCC.

**Title: High pressure crystal structures in metals**  
**Area: Condensed Matter**  
**Supervisors: Prof. Graeme Ackland and Prof. Malcolm McMahon**

This project involves using a computer package to calculate energies of various crystal structures of simple metals as observed under pressure. Prerequisites are quantum mechanics, and condensed matter physics.

Recent experimental work by McMahon has shown a panoply of different crystal structures existing under pressure. The purpose of this project is to use quantum mechanical calculation using density functional theory to shed some light on the physics behind these changes. This is done by running a pre-existing code package, so the amount of coding will be minimal.

It appears that they can be described by a simple perturbative approach to the free electron picture. This idea dates back to the 1940s and the so-called Hume-Rothery alloys: compounds with complicated structures found by tuning their chemical composition. By contrast, in the recent experiments the region of complex crystal structure is found by tuning the pressure in an elemental solid.

The hands-on work of the project will involve harnessing the power of the schools computing facilities in parallel to collect the data.

### **Aims**

The project aims to extend this understanding in the following directions

- 1) To use pre-existing code to calculate cohesive energies and band structures for various crystal structures of high pressure elements.
- 2) To evaluate relative stability of these structures from the results of these calculations, and to compare them with experiments.
- 3) To compare the results with the theory of interactions between atomic positions and the Fermi Surface.
- 4) To develop an understanding of the density functional theory as applied to solving the many-body Schroedinger equation.
- 5) To make most efficient use of distributed computing resource.

### **References**

"Origin of the complex crystal structures of elements at intermediate pressure" G.J.Ackland, and I.R.MacLeod New J.Phys 16 S2629 (2004)

"Total energy calculation of high pressure selenium: The origin of incommensurate modulations in Se-IV and the instability of proposed Se-II" Ackland GJ and Fox H J. Phys.: Condens. Matter 17 (2005) 1851-1859.

"As weird as they come."  
V Heine Nature 403, 836 - 837 (2000).

**Title: When is an iceberg not an iceberg?**  
**Area: Condensed Matter**  
**Supervisor: Prof. Simon Bates**

The structure and dynamics of liquid water -- and how these are modified by the introduction of water-loving or water-hating (hydrophilic, hydrophobic) solutes -- is of fundamental importance to a huge range of systems and processes. For many decades, the prevailing view of how hydrophobic groups were solvated by water was that water molecules located close to the hydrophobic moiety adopted an ice-like structure. This 'iceberg model' was first suggested in the 1940s on the basis of thermodynamic changes in entropy and heat capacity that had been observed experimentally. The release of structured water from the iceberg into the bulk from around the solute accounts was the mechanism that was proposed to account for these thermodynamic changes.

Modern experimental (and computational) techniques have attempted to validate or disprove this model by obtaining molecular-level insight as to how the structure and dynamics of water are modified around these solutes. But the experimental evidence is not consistent; neutron diffraction techniques show little change in the water structure around hydrophobic groups. NMR measurements show the average mobility of water molecules are reduced, but this is averaged over all water in the sample, not just those that happen to be close to the hydrophobic group. Very recently, an experimental femto-second IR study (1) has proposed that the arrangement of molecules around the hydrophobic entity is structurally like water, but dynamically like ice. The origin of this behaviour, the authors claim, is to do with the fact that waters close to a hydrophobic group are sterically prevented from adopting configurations in which they have 5 nearest neighbours, which is thought to be a signature of dynamic lability.

In this project you will use atomistic simulation techniques to computationally verify or refute this assertion. Simulations will be performed using existing codes and a variety of systems containing water and hydrophobic and hydrophilic entities. Although existing codes will be used, the project will involve code / script creation for pre- and post-processing of results, so a good level of computational ability is required.

**References:**

- 1) Resuz and Bakker, Phys. Rev. Lett. 99 148301 (2007)

**Title: Development of a robust rubric for pre-Honours laboratory assessment in Physics**  
**Area: Physics Education Research**  
**Supervisors: Dr. Ross Galloway & Prof. Simon Bates**

Laboratory work forms an integral part of the early years of almost all physical science degrees. Activity in the laboratory encompasses many simultaneous objectives, ranging from the very specific (e.g. learning how to use a particular piece of equipment) to the more general and overarching (e.g. establishment of good lab practice, completeness of data recording, clarity of expression, sophistication of error analysis, etc.) However, often for pragmatic reasons, evaluation of the degree of success of these outcomes rests on the assessment of some 'artefact', often a lab record book or report. Such assessment may fail to capture all aspects of the laboratory experience, particularly the more general qualities such as rigour and the importance of systematic approach. Furthermore, the varied aspects of the lab environment often lead to particular difficulties with consistency and validity of the assessment.

This project will seek to address some of these issues: it will begin with a detailed investigation to identify the key skills and attributes which physicists believe an undergraduate lab should foster. It will then focus on the development of a robust form of assessment for these criteria, based on the principles of constructive alignment [1]. This will feature the creation of a suitable assessment 'rubric': this is a multi-dimensional assessment mechanism which naturally incorporates multiple assessment categories, making it well-suited to the lab environment, and employs well-defined criteria for task success rather than more subjective judgements of the 'quality' of a piece of work. Thus, it should also tackle the challenging problem of ensuring consistency of assessment in large laboratory classes with many markers.

Rubrics are already in use in many areas of physics assessment, for example in the evaluation of problem solving skills [e.g. 2, 3]. This project will review existing work in this area before developing a rubric specifically focussed on the identified laboratory learning outcomes. This prototype rubric will be initially refined with reference to existing student material, before it is deployed for live trials in the first year undergraduate laboratory. The rubric will be further modified in light of preliminary evaluations in an iterative process, which will involve a rigorous statistical evaluation of its performance and direct feedback from students and markers. The intended final product of the project is a refined, validated, robust and reliable assessment instrument which can be deployed as a standard assessment system in the undergraduate laboratory.

Given the non-standard nature of this project, it is essential that interested students discuss it with the project supervisors before selection. Prior experience of education research projects is neither a requirement nor a hindrance.

References:

- 1) Biggs, J., *Higher Education*, **32**: 347-364, 1996
- 2) Docktor, J. & Heller, K., Proceedings of the 82nd NARST Annual International Conference, 2009, available online at [http://groups.physics.umn.edu/physed/People/Docktor/talks\\_papers/Docktor\\_NARST\\_09\\_paper.pdf](http://groups.physics.umn.edu/physed/People/Docktor/talks_papers/Docktor_NARST_09_paper.pdf)
- 3) Heller, P., Keith, R., & Anderson, S., *American Journal of Physics*, **60**: 627-636, 1992

**Title: The physics of consensus formation and inhibition**  
**Area: Statistical Mechanics/Condensed Matter**  
**Supervisor: Dr. Richard Blythe**

Languages of various types change over time through elements being copied (replicated), sometimes subject to alteration (mutation) - by evolution, in other words. Sometimes the outcome of this process is a stable, common language - as in the evolution of the genetic code [1] (i.e., the combination of letters on a strand of DNA that correspond to an amino acid) or the formation of the New Zealand English language dialect [2]. Generically, such ordering is referred to as "consensus", though clearly it is not always achieved.

A simple model for these evolutionary dynamics turns out to be closely related to diffusion and ordering processes in physics, and by applying techniques from nonequilibrium statistical mechanics its properties are becoming well understood [3]. However, this model is based on a number of ad-hoc assumptions - and unsurprisingly, various other models have been proposed (e.g., [4]). Some show certain consensus; others allow stable coexistence of variation.

The aim of this project is to understand more clearly under what circumstances consensus, or ordering, is achieved, and when it is inhibited. The approach could be analytical or computational - or possibly a mixture of both. The analytically-inclined student may be necessarily restricted to investigating rather simple cases, but nevertheless a thorough understanding of the stochastic equations of motion would be valuable. A more computational project would allow models involving large numbers of agents (speakers) or using more sophisticated "exemplar-based" models developed in linguistics [5] as a starting point.

In this project you will learn about stochastic dynamics and their analysis or simulation, the physics of diffusion and ordering and their applications outside physics. A student interested in a mostly computational project will need to revise (or learn) Monte Carlo simulation methods before getting to grips with the project proper.

- 1) K Vetsigian, C Woese and N Goldenfeld (2006) "Collective evolution and the genetic code" Proceedings of the National Academy of Sciences v103 pp10696-10701
- 2) G J Baxter, R A Blythe, W A Croft and A J McKane (2008), "Modeling language change: An evaluation of Trudgill's theory of the emergence of New Zealand English" To appear in Language Variation and Change, <http://www.ph.ed.ac.uk/~rblythe2/Preprints/BBCM08.pdf>
- 3) G J Baxter, R A Blythe, W A Croft and A J McKane (2006) "Utterance selection model of language change" Physical Review E v73 046118 ; G J Baxter, R A Blythe and A J McKane (2008) "Consensus and fixation on a network: A unified approach" Physical Review Letters v101 258701.
- 4) C Castellano, S Fortunato and V Loreto (2007) "Statistical physics of social dynamics" <http://arxiv.org/abs/0710.3256> ; P-Y Oudeyer and F Kaplan (2007) "Language evolution as a Darwinian process: computational studies" Cognitive Processes v8 pp21-35
- 5) J Pierrehumbert (2001) Exemplar dynamics: Word frequency, lenition, and contrast. In J. Bybee and P. Hopper (eds.) Frequency effects and the emergence of lexical structure. (John Benjamins, Amsterdam). pp137-157. [http://www.ling.northwestern.edu/~jbp/publications/exemplar\\_dynamics.pdf](http://www.ling.northwestern.edu/~jbp/publications/exemplar_dynamics.pdf)

**Title: Zeroth law for nonequilibrium steady states**  
**Area: Statistical physics/condensed matter physics**  
**Supervisor: Dr. Richard Blythe**

The laws of thermodynamics allow one to determine the macroscopic behaviour of many-body physical systems that are in thermal equilibrium with each other. The microscopic basis for these laws is provided by equilibrium statistical mechanics. Unfortunately, we do not yet have a similar system of laws, or a microscopic basis, for a system is not at thermodynamic equilibrium with its environment. These include systems that are being stirred or subjected to a driving force.

In order to understand what kind of thermodynamics might apply to nonequilibrium systems, a body of current research focuses on nonequilibrium steady states. These are systems that exhibit fluxes - for example, mass or energy fluxes - due to a driving force, but within which the fluxes themselves are time independent.

Some recent work [1] has suggested an interesting means to measure the 'temperature' of a nonequilibrium steady state, essentially by coupling it to an equilibrium system and reading off the temperature of the equilibrium system from its known equation of state. This temperature is then meaningful in that a zeroth law applies: if two nonequilibrium steady states of different temperatures are brought together, one will see a heat flux between the two nonequilibrium steady states until a new steady state (but not an equilibrium one!) is reached.

This theory relies on the assumption that connecting together an equilibrium and nonequilibrium system doesn't drag the former system out of equilibrium. The purpose of this project is to investigate this hypothesis using specific, well-studied (and exactly-solved [2]) models of nonequilibrium steady states that comprise particles being driven along a one-dimensional channel. The idea would be to construct different 'probes' that can be attached to this system as a means to measure the temperature and to understand clearly whether these probes are pulled out of equilibrium by the nonequilibrium system.

It may be possible, for simple probes, to attack this problem analytically. It is therefore well-suited to a mathematical physics student. Numerical simulation of the combined system is another methodology that is often useful: it is likely that any investigation would involve some simulation, but a more simulation-focused approach may be of interest to a computational physics student. Either way, a student taking this project would learn a lot about new ideas in statistical mechanics, and potentially contribute to our currently limited understanding of how meaningful traditional equilibrium variables like temperature are in a nonequilibrium context.

1) P Pradhan, C P Amann and U Seifert (2010) "Nonequilibrium steady states in contact: Approximate thermodynamic structure and zero-th law for driven lattice gases"  
<http://www.arxiv.org/abs/1002.4349>

2) R A Blythe and M R Evans (2007) "Nonequilibrium steady states of matrix-product form: a solver's guide" J Phys A: Math Theory v40 R333

**Title:** Does the climate system work such as to generate maximum entropy?  
**Area:** Statistical mechanics, atmospheric dynamics  
**Supervisors:** Prof. Simon Tett and Prof. Ian Main

In the 1970's Paltridge (1974, 1978) published a set of papers in which he built a simple thermodynamic model of the Earth's climate. He parameterised the horizontal transports of heat using the assumption that the transports would act to maximise entropy production (MEP) by the Earth system, and found good agreement with observations of the temperature profile from equator to pole. Recently Dewar (2003, 2005) claimed to have proven that MEP arises from statistical-mechanical constraints of conservation of energy and mass in an open system. Martyushev and Seleznev, 2006 reviewed earlier work in deriving the concept, highlighting MEP is always subordinate to stronger constraints in realistic applications in physics, chemistry and biology. There is ongoing controversy over whether, or not, the MEP hypothesis applies to the Earth-system (Goody, 2007; Ozawa et al, 2003; Paltridge, 2007).

Analysis of the atmospheric state has been carried out in which models have "assimilated" observations for several decades. In data assimilation observations and models are brought together to give a self-consistent analysis of the observations. The most recent of these is the ECMWF reanalysis (Uppala et al, 2005). The aim of the project is to use data from this reanalysis to see if the MEP is acting on large space and time scales in the atmospheric circulation with the eventual aim of using MEP as a constraint (in the absence of others) in undetermined problems such as the effect of sub-grid scale processes on large scale flows

#### References

- Dewar, RC, 2005 Maximum entropy production and the fluctuation theorem, Journal of physics A. DOI: 10.1088/0305-4470/38/21/L01
- Dewar, RC, 2003 Information theory explanation of the fluctuation theorem, maximum entropy production and self-organized criticality in non-equilibrium stationary states, Journal of Physics A: 36, 631-641.
- Goody, R., 2007: Maximum Entropy Production in Climate Theory. Journal of the Atmospheric Sciences: 64 2735-2739
- Martyushev, LM and VD Seleznev, Maximum entropy production principle in physics, chemistry and biology, Physics Reports 426(1) 1-45. DOI: 10.1016/j.physrep.2005.12.001
- Ozawa, H et al, 2003: The second law of thermodynamics and the global climate system: A review of the Maximum Entropy Production Principle. Reviews of Geophysics doi: 10.1029/2002RG000113
- Paltridge, GW; Farquhar, GD; Cuntz, M [Maximum Entropy Production, Cloud Feedback, And Climate Change](#) GEOPHYSICAL RESEARCH LETTERS, 34 (14): Art. No. L14708 JUL 26 2007
- Paltridge, GW [Steady-State Format Of Global Climate](#). Quarterly Journal of The Royal Meteorological Society, 104 (442): 927-945 1978
- Paltridge, GW [Global Dynamics And Climate - System Of Minimum Entropy Exchange](#) Quarterly Journal Of The Royal Meteorological Society, 101 (429): 475-484 1975
- Uppala, SM et al, 2005: The ERA-40 re-analysis, Quarterly Journal of The Royal Meteorological Society, 131 (612): 2961-3012

Keywords: Statistical mechanics, atmospheric dynamics

Additional Comments: Would suit a computationally literate and numerate student.

**Title: The impact of geo-engineering on the hydrological cycle**  
**Area: Climate change, climate modelling, geo-engineering**  
**Supervisors: Prof. Simon Tett and Dr Gabi Hegerl**

Several scientists think that it may be time to consider geo-engineering the climate in order to reduce climate change. One idea puts small particles into the atmosphere to reflect incoming solar radiation back to space and thus cool the planet. Another idea is to put giant mirrors in space to reflect some solar radiation away. These approaches involve large financial investment and their potential climatic impacts are poorly understood. Consequently, before implementing any geo-engineering approach it is important to quantify the climatic effects of possible approaches.

The two ideas outlined above are an attempt to offset greenhouse gas warming by reducing the amount of solar radiation that reaches the lower atmosphere. Changes in greenhouse gases are less effective in driving changes in global-scale evaporation than are changes in solar radiation. So reducing solar radiation to compensate the effect of greenhouse gases is likely to cause a reduction in global-scale evaporation and thus global-scale precipitation.

Further, the warming effect of greenhouse gases is relatively uniform while reducing solar radiation has largest effect in the tropics where, annually-averaged, there is more incoming solar radiation per meter squared. This may induce north/south temperature differences and affect the transport of water vapour from equatorial regions to extra-tropical regions.

The student would use the Hadley Centre's HadCM3 global climate model to assess the sensitivity of the hydrological cycle to proposed geo-engineering approaches. The student, with support, would be expected to set up, run and analyse numerical experiments to see what impact some proposed geo-engineering proposals would have on the hydrological cycle.

Keywords: Climate change, climate modelling, geo-engineering.

Additional Comments: Would suit a reasonably numerate student.

**Title:** The dependence of simulated tracer transport in the Antarctic polar vortex on model resolution  
**Area:** Climate Physics  
**Supervisors:** Dr. David Stevenson, Dr. Hugh Pumphrey, Dr. Sebastian Rast, Dr. Hauke Schmidt

The simulation of the Antarctic ozone hole is still unsatisfactory in many chemistry climate models (CCMs). Frequently, too weak ozone depletion is simulated for Antarctic spring. This is true, e.g., for different chemistry climate models based on the general circulation model ECHAM5. The simulation of the ozone hole depends on the interplay of many model components, in particular gas phase and heterogeneous chemistry schemes, tracer transport schemes, radiation, and dynamics. Most CCM simulations are performed with a relatively coarse model resolution of, in the horizontal dimensions, typically a few degrees in the case of finite volume models, or a spectral truncation at wave numbers not larger than 42 (T42). This can lead to two problems with respect to tracer transport involved in ozone depletion: a) Numerical diffusion is in general large for coarse model resolutions, so that transport through the vortex edge is overestimated, and b) The resolution of synoptic scale waves in the tropopause region is insufficient which may have an impact on the general vortex dynamics and in particular vertical transport in the lowermost stratosphere.

This project is intended to study the dependence of tracer transport in the Antarctic polar vortex on model resolution. To this end, a suite of numerical simulations with the ECHAM5 GCM at different model resolutions (T31, T63, T127, and T255) will be analyzed. In these simulations a small number of passive tracers will be initiated early in Antarctic winter at different height levels inside and outside the vortex. Numerical diffusion and vertical transport will be analyzed, compared for the different model resolutions, and the implications for ozone hole simulations will be discussed.

**Title:           The composition of the mesosphere using ground-based mm-wave remote sensing**  
**Area:            Atmospheric physics**  
**Supervisor:   Dr. Hugh Pumphrey**

The mesosphere, lying at altitudes between 50 and 80 km, is one of the least-understood regions of the atmosphere. One way to study its composition is to use a millimetre-wave receiver (essentially a radio telescope) sited on the ground (preferably on a high mountain).

The spectra from such an instrument can provide information on the mixing ratio of a variety of chemical species of interest. Recent improvements in technology are permitting easier access to higher frequencies.

This, then, poses these questions: which species might one usefully measure with this technique? What characteristics (bandwidth, resolution, noise level) would a spectrometer require in order to make the measurement? How badly affected would the measurement be by a wet troposphere (and hence, how high a mountain would you need)?

The basic technique of the project is to simulate a measurement using a readily-available radiative-transfer model (ARTS: see <http://www.sat.ltu.se/arts>) and apply the standard techniques of inverse theory[1] to the simulation to determine what information the measurements would contain.

Several projects along these lines would be possible, to answer such questions as:

- (1) Which of the various absorption lines of CO is most suitable for sounding the mesosphere?
- (2) Is it possible to use ground-based sensing of HCl to track the chlorine loading of the middle atmosphere?

References:

[1] Inverse Methods for Atmospheric Sounding: Theory and practise by Clive D. Rodgers (World Scientific, ISBN 981-02-2740-X)

**Title: Using aircraft and satellite data to estimate sources of CO, CO<sub>2</sub> and CH<sub>4</sub> from Canadian forest fires during summer 2010**  
**Area: Atmospheric physics**  
**Supervisor: Prof. Paul Palmer**

The burning of boreal forests, of which approximately 5 to 20 million hectares burn annually (mainly in Russia and North America), removes vegetation, changes land-surface properties, and emits trace gases, aerosols, and smoke in prodigious quantities. Consequently, wildfires are amongst the most important global contributors to a number of key atmospheric species (e.g., CO<sub>2</sub>, CH<sub>4</sub>, CO, NO<sub>x</sub>, black carbon) and their long-range transport impact Earth's radiation budget, air quality and processes such as tropospheric O<sub>3</sub> production far from the source region.

The University of Edinburgh leads the BORTAS project ([www.geos.ed.ac.uk/eochem/bortas/](http://www.geos.ed.ac.uk/eochem/bortas/)) to investigate the connection between the composition and distribution of biomass burning outflow, O<sub>3</sub> production and loss with that outflow, and the resulting perturbation to chemistry in the troposphere. The focal point of the project is a 3-week aircraft campaign over the North Atlantic during July 2010 (seasonal peak of Canadian forest fires), which involves additional measurements over mainland Canada and the Azores. One of our main analysis tools to interpret these data is the GEOS-Chem global 3-D chemistry transport model (<http://www.geos-chem.org/>), which relates surface sources and sinks of gases and particles to atmospheric concentrations.

This project will include (1) the interpretation of observed concentration observations of CO<sub>2</sub>, CH<sub>4</sub>, CO during BORTAS using the GEOS-Chem model; and (2) the application of an optimal estimation inverse model to estimate the sources and sinks of these trace gases from the observed concentration measurements. The candidate will also use satellite observations of atmospheric chemistry and land-surface properties to help interpret the spatial and temporal distribution of burning emissions over North America during BORTAS. The project will involve computer programming and data analysis.

**Title: Nucleation in Biological Systems**  
**Area: Macromolecular Physics/ Biological Physics**  
**Supervisors: Dr. Cait MacPhee and Dr. Line Jourdain**

A quick glance at wikipedia suggests that “nucleation” is a physical process involving the onset of crystal formation in a supersaturated liquid. The same term is also commonly applied to the mechanism underlying the onset of protein self-assembly and aggregation in biological systems. Such self-assembly and aggregation is of interest as it underlies a range of human and animal disorders such as “Mad Cow Disease” and the human equivalent Creutzfeldt-Jacob Disease, as well as adult-onset diabetes. But is this initiation of aggregation really “nucleation” in the classical sense, and can we make sense of it in the inherently messy environment of biology?

You will look at nucleation of protein aggregation using a model protein system. This project will involve using high through-put fluorescence methods to perform (concurrently) the large number of identical experiments required to obtain the good statistics necessary to recognise and analyse rare events. You will also use simple fitting and modelling packages to extract the maximum meaningful information from this data set. Your results will be compared with existing data obtained for another protein, and you will help to develop a robust and general model of “nucleation” in these systems.

For further information, see:

Chiti et al (2006) *Ann Rev Biochem* 75: 333-366

Auer et al. (2008) *Phys Rev Lett* 101: 258101

Tessier and Lindquist (2007) *Nature* 447: 556-

**Title: The influence of interfacial particles on the Marangoni instability**  
**Area: Soft Condensed Matter Experiment**  
**Supervisor: Dr. Paul Clegg**

Colloidal particles can become trapped on the interface between two immiscible liquids (like oil and water). This behaviour has similarities and differences to conventional surfactants (like soap). For example, both can be used to stabilize droplets of oil in water to make an emulsion [1]. When an interface is densely packed with particles it becomes rigid – and this is very different to the behaviour of soap.

In this project you will trap particles on the interface between oil and water and you will explore how they modify the movement of a third liquid (an alcohol) as it is transferred from the oil to the water. In this situation various phenomena can occur – including the Marangoni instability and spontaneous emulsification [2]. You will see how these are modified by the presence of interfacial particles [3]. Experiments will be carried out in a Langmuir trough where the area fraction of particles can be systematically controlled. Successful completion of this project is likely to result in a publication.

- 1) B.P. Binks and T.S. Horozov, *Colloidal particles at liquid interfaces* (CUP, Cambridge, 2006)
- 2) J.T. Davis and E.K. Rideal, *Interfacial Phenomena* (AP, New York, 1961)
- 3) D. Vella et al. *Phys. Rev. Lett.* **96**, 178301 (2006).

**Title: Atomic force microscopy on polymer coated surfaces**  
**Area: Soft Condensed Matter**  
**Supervisors: Dr. N. T. Pham and Dr. D. Marenduzzo**

Atomic force microscopes (AFMs) are relatively new powerful tools to “view” nanometer-to-micron size objects and estimate the forces characterising their mutual interaction.

In this project you will first use an AFM to probe the physical behaviour of a surface coated with PEG (poly-ethylene-glycol), a hydrophilic molecule a few nanometers in length, which is often used in biophysical assays to prevent non-specific adhesion of biomolecules. The AFM we have in the School of Physics will allow measurements of the force felt by its tip upon approaching the polymer coated surface. With a 'naked' tip, we expect to measure a repulsive force which you will compare with theoretical predictions coming from a simulation code developed by D. Marenduzzo here in Physics. Can we read off from the force curve the extent of PEG packing? Is the signal you observe sensitive to changes in the salt composition of the buffer?

In the second part of the project, you will probe the PEGylated surface with an AFM tip covered with (*Escherichia coli*), again with different choices for the salt composition of the buffer. We will use the method developed in [1] to study the interaction between the bacteria on the tip and the PEG surface, with a view of devising a technique to control the adhesion of bacteria to a wall and hence the formation of biofilms. The nature (attractive or repulsive) and extent (in nano-Newtons) of the interaction between PEG and bacteria will leave a signature in the force-extension AFM curves. We would like to infer this from the comparison between simulations (in which we can vary at will the interaction potential) and experiments.

We expect that this project if successful will lead to a publication in a scientific journal.

**References:**

- 1) A. Razatos {*et al.*}, *Force measurements between bacteria and poly(ethylene glycol)-coated surfaces*, *Langmuir* **16**, 9155 (2000).

**Title: Spatial characterisation of bacteria colonies**  
**Area: Condensed Matter**  
**Supervisors: Prof. Wilson Poon, Drs. Davide Marenduzzo and Tiffany Wood**

Colony morphology is one way in which scientists identify the strain of bacteria that form a colony. Under a microscope colonies can appear circular in shape, filamentous or irregular. We would like to understand how physical parameters such as the aspect ratio of bacteria, Brownian motion and interactions between bacteria and with substrate can influence the spatial characteristics of bacteria colonies.

In this project you will track the growth of bacteria colonies under an optical microscope. Factors such as the strain of bacteria and the substrate may be varied. Images will be analysed and the spatial characteristics of the colony will be quantified by the local order parameter (familiar from the physics of nematic liquid crystals). Simulations may also be run (using existing code) to quantify the relative importance of various physical parameters for the conditions studied.

**Title: Quantifying the motility of microorganisms**  
**Area: Condensed Matter**  
**Supervisors: Prof. Wilson Poon and Dr. Vincent Martinez**

Motility is a key characteristics of life, and is present even in the simplest single-cellular organisms, such as bacteria, amoeba and algae. Quantifying such motility is an essential part of biophysics. In this project, you will use two new, microscope-based methods invented here in Edinburgh to study the motility of bacteria (and perhaps other microorganisms). The project can develop in two broad directions. On the one hand, you may wish to concentrate on studying the methods themselves, e.g. figuring out how to extract more accurate information from the data. Or you may want to use the methods in their current state and study motility in unusual environments, e.g. bacteria swimming in polymer solutions.

**Title: Polymer-induced aggregation of bacteria**  
**Area: Condensed Matter**  
**Supervisors: Prof. Wilson Poon and Dr. Jana Schwarz-Linek**

Bacteria find themselves in the presence of polymer in many natural and biotechnological situations. Polymers can induced bacteria to aggregate by a variety of mechanisms, none of which is properly understood. In this project, you have the opportunity to investigate some of the open issues in this field. For example, it is thourhgt that polyvalent ions (such as  $\text{Ca}^{2+}$ ) may play a vital role (in 'bridging' negatively charged polymers and bacteria) in aggregation, so that you may want to investigate polymer-induced aggregation in the presence of such ions. Another project is to study how the aggregation of motile and non-motile bacteria differ. Preliminary results suggest that clusters of motile bacteria develop a spontaneous rotation (they are 'micro-motors!'). The principal methods will include time-lapsed photography, microscopy and image analysis.

**Title: The Effect of Molecular Anchoring on the Rheology of Liquid Crystals**  
**Area: Condensed Matter**  
**Supervisors: Prof. Wilson Poon and Dr Tiffany Wood**

Liquid crystals exhibit unusual rheological properties due to competition between elastic forces that align the molecules along the flow direction and the strength of molecular anchoring at the surfaces of the substrate applying the shear. The influence of molecular anchoring on the flow properties has not yet been investigated experimentally. Molecular anchoring can be controlled by treating substrates with Lecithin, an egg white protein, the concentration of which can be used to vary the anchoring strength from  $10^{-5}$  to  $10^{-3}$  J/m<sup>2</sup>. In this project you will use a rheometer to investigate the effect of the liquid crystal anchoring strength on the substrate on the bulk rheological properties.

**Title: Colloid dispersions in a Nematic Liquid Crystal**  
**Area: Condensed Matter**  
**Supervisors: Prof. Wilson Poon and Dr Tiffany Wood**

In the limit of weak anchoring recent work has shown that colloid dispersions in a nematic liquid crystal form a stiff gel at volume fractions higher than 20%. The elasticity of the gel arises from a network of line defects that become entangled above this volume fraction. Simulations have shown that the disclinations take on an 'entangled point defect' configuration.

For higher anchoring strength at the particle surface simulations indicate that disclinations take on a different form, 'the figure of eight' defect. Predictions show that this drives the colloids to self-assemble into planes rather than three dimensional structures. Because there is less disorder in the nematic phase associated with this defect it is likely that this material will be less stiff. This project will involve the dispersion of colloids coated with Lecithin which promotes relatively strong anchoring. The viscous and elastic moduli will be measured using a rheometer and compared with existing data for the weak anchoring case. Confocal microscopy will also be carried out to investigate the structure of these dispersions.

**Title: Anisotropic colloid coatings**  
**Area: Condensed Matter**  
**Supervisors: Prof. Wilson Poon and Dr Tiffany Wood**

There is considerable interest currently in the self-assembly of colloids for the construction of large scale structures and devices. We would like to investigate whether the self-assembly of colloids can be controlled by liquid crystal coatings. Liquid crystals prefer to align along a preferred direction known as the director. It is necessary for defects to form when a liquid crystal coats a spherical particle. It is probable that two particles coated in a nematic phase would bind when the defects approach one another but repel when aligned and highly-curved surfaces approach one another. This project involves an experimental investigation of the use of liquid crystals for the self assembly of nano- and micro-particles. It is likely that particle size will have a strong influence over the self-assembled structure.

**Title: Rheology of passive and active liquid crystalline gels**  
**Area: Soft Condensed Matter**  
**Supervisors: Dr. E. Sanz, Dr. D. Marenduzzo and Prof. M. E. Cates**

Liquid crystalline phases are a remarkable example of soft materials: their properties are intermediate between those of solids and of liquids. They possess long range orientational order and elastic responses to shear like solids, yet they can flow like fluids. Examples of liquid crystals include nematics (in which the molecules are on average parallel to each other), and cholesterics (in which the average orientation in addition develops a helical pitch). A particularly trendy kind of liquid crystals are fish schools or concentrated bacterial suspensions. In these cases the constituents are alive and they can swim, as well as being advected by any flow, and the hydrodynamic model theory which aims at elucidating their long range behaviour is referred to as active liquid crystal theory.

In this project you will use a Lattice Boltzmann algorithm, which we have coded up and optimised in Edinburgh, to study the dynamics of a liquid crystalline gel when it is subjected to a linear or oscillatory shear. The study of these flow properties is referred to in soft matter physics as "rheology". The code in Edinburgh allow us to study either the rheology between walls or in the bulk (by means of appropriate boundary conditions for the velocity field). There are several important liquid crystals for which the rheological properties are still poorly characterised, and you will contribute to fill this gap if you take on this project!

Possible systems to be studied are:

- 1) Nematic liquid crystals under the combined influence of an electric field and a shear flow;
- 2) Cholesteric liquid crystals subjected to flow along the axis of their helical twist (so-called permeation flow);
- 3) Bulk shear flow of active liquid crystalline gels.

There could be further possibilities as well. This project is suitable either to motivated students interested in computational physics, or to students interested in soft condensed matter and willing to engage with a code.

**Title: Statistical physics of active materials**  
**Area: Non-equilibrium statistical physics, soft condensed matter, computational physics and modelling**  
**Supervisors: Dr. D. Marenduzzo and Dr. C. Valeriani**

Suspensions of bacterial swimmers, cell extracts and colonies of microorganisms are examples of active matter. These are systems which exploit energy coming from the environment, e.g. in the form of ATP, in order to self propel or perform other kinds of functions. Active matter is very interesting for physicists as it is inherently out of equilibrium, even in steady state, due to its continuous energy intake.

In this project we would like to study the statistical and physical properties of a model for active matter. In its original form, the model is due to Vicsek [1], and is now well studied in the community of theoretical biophysics. The Vicsek model may be seen as a simple model for bacterial fluids, in which individual agents move and interact to locally align their velocities, and are also subjected to the influence of noise, which tends to destroy any orientational order.

First, we would like to reproduce the original phase transition with a computer based code of the Vicsek model. We would then like to generalise the model to study the behaviour of a mixture in which a few colloidal hard spheres are immersed in this "bacterial" bath. The aim is to characterise the fluctuations and motion of these colloidal diffusing obstacles, and to compare with in-house existing data which suggest the presence of several interesting dynamical regimes as a function of time and density.

If time permits, we would also like to study the phase behaviour of a mixture of polymer and bacteria, modelling the latter by Vicsek active particles, and the former by soft spheres. We want to ask, is there a non-equilibrium phase separation between movers and passive spheres? What are the effects of confining walls?

In the world of passive colloids, binary mixture lead to interesting effects such as aggregation caused by entropy depletion. What is the analog of this behaviour in such an active non-equilibrium system?

In this project you will have the opportunity to learn a lot on the theory of activematter, which is currently a very hot topic in statistical physics and biophysics, and you will have the chance to research new topics in this field.

[1] T. Vicsek et al., Phys. Rev. Lett. 75, 1226 (1995).

**Title:** Czochochalski growth of the large single crystals to study quantum criticality.  
**Area:** Hard Condensed Matter Experiment.  
**Supervisors:** Prof. A D Huxley and Dr. D A Sokolov

At very low temperatures ( $T < 1\text{K}$ ) the majority of solids are either magnetically ordered or superconductors. Conventional superconductivity is normally mediated by the interaction of electrons with the vibrations of the crystal lattice (phonons) and is well described by the Bardeen Cooper Schrieffer (BCS) theory. However, in some antiferromagnetic and ferromagnetic materials unconventional forms of superconductivity have been observed within magnetically ordered states [1]. A common feature of these materials is the low critical temperature of a magnetic transition; for antiferromagnets the magnetic transition is the onset of anti-magnetic order. This suggests that quantum critical zero-point fluctuations of the magnetisation may provide the pairing interaction that mediates superconductivity rather than lattice vibrations. However, since small changes of the lattice parameter give large changes of the magnetic moment a phonon mechanism to explain superconductivity that is subtler than that described by BCS cannot be ruled out. Different theoretical models to describe what might happen are hotly debated. Experiments to measure the spectra of both phonons and magnetic fluctuations should identify which mechanism plays the key role in forming the unconventional superconductivity. So far, worldwide, most effort has been applied to compounds containing 5f electrons that owing to the coincidence of different energy scales are difficult to model theoretically. The plan for the present project is to look at analogous materials with 4f electrons that should reduce these difficulties. PrNiGe is a good candidate for this study.

In this project you will synthesize PrNiGe and study the effects of pressure and magnetic field on its magnetism. The most direct way to study magnetic ordering and magnetic fluctuations in solids is by measuring neutron scattering. The neutron is an excellent probe since its magnetic interaction with matter is weak so that it does not disturb the system being measured and it is sensitive to energy transfers of the relevant magnitudes. The downside is that large samples and a large incident neutron flux is required to generate sufficient scattering. The requirement for a large neutron flux is addressed by performing measurements at central facilities.

This project will focus on growing the required large (dimension  $\sim 2\text{cm}$ ) high quality single crystal of the antiferromagnet PrNiGe. This will be combined with studies of the effect of magnetic field on its magnetic/electronic properties to map out the low-temperature phase diagram to decide under which conditions the neutron scattering measurements should be made.

The crystals will be grown using the Czochochalski pulling method. The crystals will then be oriented using the Laue X-ray method and cut to suit the geometry required for measurements. Characterization of the oriented single crystals will include studies of the anisotropy of thermodynamic quantities such as field dependent heat capacity, magnetization, magnetic susceptibility and also electrical resistivity using the state of the art experimental facilities at CSEC (in the JCMB) and at St. Andrews University. The magnetic and thermodynamic measurements will be analysed and compared with theoretical predictions for quantum critical behaviour. Once large high quality single crystals have been made and characterised, neutron scattering experiments will follow. Performing the neutron experiments within the scope of the MPhys is a possibility, but subject to scheduling constraints.

Growth of the single crystals and their characterization will be performed in CSEC, neutron scattering experiments will be carried out at ISIS in Oxfordshire and/or the ILL in Grenoble, France. We expect to publish the results in a peer-reviewed journal.

The project is naturally extendable into a PhD project.

**Prerequisites:** Familiarity with basic concepts of Solid State Physics.

**References:** [1] F. Levy, et al., Science 309, 1343, (2005).

**Title: Properties of the thermoelectric alloy Bismuth Telluride**  
**Area: Hard Condensed matter experiment and theory**  
**Supervisor : Dr. Robin Perry**

Thermoelectric power cells offer the potential of clean electricity generation from waste heat production. They are essentially electronically conducting materials that have poor thermal conductivity. Good thermoelectric materials have large thermopower or Seebeck coefficients. The Seebeck effect is the voltage drop across a material when it is placed in a temperature gradient and the polarity depends on the charge of electric carrier; hole or electron. Hence the major application for these materials in the energy sector would be conversion of waste heat into electric power. Indeed, since they are good thermal insulators, they could even be used to both insulate and power your home! The concept of thermoelectric power generation is not new but its full realization has been hampered by a lack of suitable materials.

One of the best known materials bismuth telluride  $\text{Bi}_2\text{Te}_3$  was discovered in the 1960's. It is also the material most used in thermoelectric applications by industry.

The project will involve:

1. Synthesizing polycrystal  $\text{Bi}_2\text{Te}_3$  by a conventional metal-alloying technique.
2. Either X-ray characterization or Energy dispersive X-ray analysis of the material to confirm the chemical structure.
3. Cutting and polishing the sample for measurement.
4. Measurement of the Seebeck coefficient using the Quantum Design PPMS system. This equipment is already installed and operates as a user-facility in the Centre for Science at Extreme Conditions (CSEC) building.

If time permits, the project can be extended to include doping the material with Antimony or Selenium to tune the properties.

We are also very interested in modeling the electronic structure of this material. Thermoelectric properties are governed almost entirely by the electron band structure hence understanding this in  $\text{Bi}_2\text{Te}_3$  can give us a valuable insight into how to design new and better thermoelectric materials. Students who are more theoretically minded might be interested in pursuing this direction instead of material preparation.

**Prerequisites:** Familiarity with the basic concepts of Solid State physics.

**Title: America Sucks**  
**Area: Computational/Mathematical - based in CPlab.**  
**Supervisor: Prof. Graeme Ackland**

In a previous project, we investigated the spread of a beneficial technology across various continents based on a reaction-diffusion model not unlike the FKPP equation <http://www.ph.ed.ac.uk/~gja/Neolithic/copy/Neolithic.html>

In this project we extend the work to look at North America. While in other areas the expansion of farming brought a wave of population increase across continents, the first arrival of humans in America was accompanied by a mass extinction of most of the prey species - exterminating their prey meant that the early Americans (Clovis people) always had more favourable environments ahead of them. Hence the Clovis expansion is remarkably fast as the people are sucked across the continent. Within the FKPP framework, this requires an additional coupling between environment and exploitation.

The project will require excellent java coding and data handling skills, and reasonable mathematical ability to cope with the stability of solitary wavefronts.

**Title: Explosive nucleosynthesis network calculations**  
**Area: Centre for Science at Extreme Conditions**  
**Supervisors: Dr. Alex Murphy and Prof. Graeme Ackland**

This project involves the creation of a network calculation suitable for tracking the evolution of isotopic abundances during explosive nucleosynthesis, such as that which occurs in novae and X-ray bursters.

### **Outline**

Novae and X-ray bursts occur when hydrogen from one star accretes on to the surface of a compact companion star consisting of previously evolved material (typically carbon, oxygen and neon). The density and temperature of the accreted material rises, and as it reaches criticality thermonuclear runaway occurs. Energy liberated in nuclear reactions result in heat that alters the temperature and density of the burning environment, and thus the subsequent nuclear reaction rate. Determining the overall nucleosynthesis and energy release is thus complicated. Simulations involve tracking the evolution of the isotopes as a function of time with inputs of the temperature and density and the network of nuclear reactions available. The aim of this project is to develop a one-dimensional simulation of an explosive environment and illustrate the general features of such astrophysical events.

### **Project objectives:**

- 1) Familiarise yourself with the principles of nucleosynthesis, the reactions which can happen. Do a literature search to find the rate constants for the various reactions and for the initial conditions of the environment.
- 2) Write a computer code for a set of differential equations describing the concentration of each component, and integrate it forward in time to find the change of composition as time proceeds. Implement this within a one-dimensional model of a compact stellar remnant.
- 3) compare your results with the observed luminosities and abundances occurring in novae and/or X-ray bursters. Explore the behaviour of your results on the initial conditions.

### **Skills**

The project will require a significant amount of programming. Literature survey, data handling skills, and analysis will be necessary. This is a research project, developing a tool that could be of use in determining the significance of laboratory measured nuclear reaction rates.

**Title: Crystal Structures of Planetary Ices**  
**Area: Centre for Science at Extreme Conditions**  
**Supervisor: Dr. J Loveday**

The outer planets (Jupiter, Saturn, Neptune, Uranus and Pluto) and their satellites contain significant fractions of ices (water-ice, methane and ammonia). As a result these ices are minerals in the context of the outer solar system and their high-pressure properties provide crucial information for the modelling of the outer solar system.

The project will focus on the high-pressure properties of ammonia and methane hydrates which are the main icy components of Saturn's largest moon Titan which was recently visited by the Cassini/Huygens space mission. In house x-ray studies using diamond anvil cells will be used to solve the high-pressure crystal structures along with Raman scattering studies of dynamic properties. There may also be possibilities for neutron and synchrotron diffraction studies using central facilities.

**Title: Electronic Music Synthesis Using CSOUND**  
**Area: Acoustics**  
**Supervisors: Prof. C A Greated and Dr. Stefan Bilbao**

Physical modelling techniques are now becoming widely used for the synthesis of musical tones. These model the physical processes that take place in the production of the sound rather than the more ad-hoc methods associated with more conventional synthesis techniques such as frequency modulation and wave shaping. A physical model will be formulated to simulate percussion sounds, particularly the xylophone, and this will be implemented using CSOUND, a program specifically devised for sound synthesis. The first part of the project will involve an analysis of actual sounds from an instrument using conventional signal processing techniques such as spectral analysis. The final submission will include a CD containing fragments of actual and synthesized sounds.

### **References**

- 1) The CSOUND book, edited by Richard Boulanger, MIT Press 2000
- 2) Murray Campbell and Clive Greated, "The Musician's Guide to Acoustics", Oxford University Press
- 3) Murray Campbell, Clive Greated and Arnold Myers, "Musical Instruments", Oxford University Press 2004
- 4) C Dodge and T A Jerse, "Computer Music", Schirmer 1985
- 5) Curtis Roads, "The Computer Music Tutorial", MIT Press 1996

**Title: Acoustic Pulse Reflectometry**  
**Area: Acoustics**  
**Supervisors: Prof. D M Campbell and Prof. C Greated**

Acoustic pulse reflectometry is a technique by which the internal bore profile of a duct of cylindrical symmetry can be reconstructed from measurements of the reflection of an acoustic pulse. In a typical reflectometer, a loudspeaker generates a short pressure pulse which passes down a cylindrical source tube several metres long. A microphone is embedded in the wall at an intermediate position along the source tube. At the end of the source tube the pulse is injected into the duct under investigation. Each change in the diameter of the duct generates a partial reflection of the pulse; the reflections travel back through the duct and are recorded by the microphone. By using a suitable algorithm, which takes into account multiple reflections and losses, it is possible to reconstruct the axial variation of the duct diameter. The acoustical response function of the duct can also be derived, either in the time domain (the input impulse response) or the frequency domain (the input impedance). The technique has found numerous industrial and medical applications, and has proved useful in the study of musical wind instruments.

The project involves setting up an acoustic pulse reflectometer in which the acoustic pulse is generated by a computer-controlled compression driver. The effect of different pulse shapes on the accuracy of the reconstructions will be investigated for a number of ducts, including specially constructed test systems and musical instruments.

**References:**

- 1) Sharp, D. B., "Acoustic pulse reflectometry for the measurement of musical wind instruments", PhD thesis, University of Edinburgh (1996).
- 2) Sharp, D. B. and Campbell, D. M., "Leak detection in pipes using acoustic pulse reflectometry", *Acustica* 83 (1997), 560-566.
- 3) Sharp, D. B., "Increasing the length of tubular objects that can be measured using acoustic pulse reflectometry", *Meas.Sci.Tech.* 9 (1998), 1469-1479.
- 4) Kemp, J. A., "Theoretical and experimental study of wave propagation in brass musical instruments", PhD thesis, University of Edinburgh, 2002.
- 5) Buick, J. M., Kemp, J., Sharp, D. B., van Walstijn, M., Campbell, D. M., Smith, R. A., "Distinguishing between similar tubular objects using pulse reflectometry: a study of trumpet and cornet lead pipes", *Meas.Sci.Technol.* 13 (2002), 750-757.

**Title: Non-Linear Dynamics of an Artificially Blown Trumpet**  
**Area: Acoustics**  
**Supervisors: Prof. D M Campbell and Prof. C Greated**

Sound is generated in a lip-driven musical instrument (such as a trumpet) by self sustained oscillations in the air column of the instrument. These oscillations are induced by aero-elastic coupling between a mechanical oscillator (the lips of the player) and the acoustic resonator formed by the air column. The behaviour of the resulting coupled system is an interesting problem in non-linear dynamics. Several musically important aspects of the operation of the system are not yet fully understood. This project involves setting up an apparatus in which a pair of artificial lips are used to play a trumpet. The mechanical vibrations of the lips and the acoustical oscillations of the air column will be measured while the instrument is sounding, and the behaviour compared with the predictions of a computer model.

**References:**

- 1) Gilbert, J., Ponthus, S., Petiot, J-F., "Artificial buzzing lips and brass instruments: experimental results", *Journal of the Acoustical Society of America* 104 (1998), 1627-1632.
- 2) Cullen, J. S., Gilbert, J., Campbell, D. M., "Brass instruments: Linear stability analysis and experiments with an artificial mouth", *Acustica united with acta acustica* 86 (2000), 704-724.
- 3) M Campbell, "Brass instruments as we know them today", *Acta Acustica united with Acustica* 90 (2004), 600-610.

**Title: In-depth study of a nuclear reaction process for Nuclear Astrophysics**  
**Area: Experimental Nuclear Physics**  
**Supervisor: Dr. M Aliotta**

Much of modern Nuclear (Astro-)Physics experiments are carried out at dedicated international facilities, where “beam time” allocation involves a highly competitive process among different experimental groups around the world. In order to secure “running time” the experiment has to be sound and well thought out. A careful investigation of all the aspects involved at the experimental stage must therefore be foreseen at a preliminary stage, well before the actual experiment takes place. Typical procedures for beam time application require the writing up of a detailed experimental proposal to be submitted to the relevant scientific committee for evaluation. The project consists in the in-depth study of a nuclear reaction of astrophysical relevance with the implication that the final report may be used as a basis for a research proposal to be submitted at international facilities for an actual experiment.

The project involves the following aspects:

- 1) literature research on a reaction of current astrophysical relevance
- 2) investigation of experimental approach to be used
- 3) writing up a proposal for submission to international scientific committees

Key aspects of the proposal will be:

- 1) scientific relevance of the nuclear reaction to be studied
- 2) experimental methodology envisaged
- 3) design and description of experimental setup to be used
- 4) analysis method to be employed
- 5) justification of beam time request

Depending on the quality of the proposal produced as well as on the student’s interest, the project may represent a natural starting point leading to a PhD project.

**Requisites for this project:**

- 1) attendance to the courses on Nuclear Physics (3rd and 4th year)
- 2) research-oriented attitude and interest
- 3) potential interest for a PhD in experimental Nuclear Astrophysics

**References:**

- 1) C.E. Rolfs and W.S. Rodney: *Cauldrons in the Cosmos*, University of Chicago Press, 1988
- 2) Various review articles  
Previous accepted research proposals (provided by supervisor)

**Title:           The setup of a Compton Camera for directional gamma-ray detection**  
**Area:           Nuclear Physics**  
**Supervisor:   Dr. Daniel Watts**

Electronically collimated gamma cameras based on Compton scattering have great potential to improve imaging of radio isotope labelled organs in medicine and bio-medical research. The basic idea of a Compton camera is to replace mechanical photon collimators, which are necessary to get directional information on the gamma rays, with electronic collimation using the Compton effect. This solution has potential to eliminate the large losses of photon flux associated with mechanical collimators. A Compton camera consists of two detectors: a Compton scatter detector and a position sensitive crystal scintillator. Photons emitted from the sample undergo Compton scattering with electrons in the material of the scatter detector where the position and kinetic energy of the recoil electrons are measured. The scattered photons subsequently undergo photo-absorption inside the crystal scintillator where their position and total energy are measured. The project will involve the setup of a prototype Compton camera including an investigation of the merits of using various possible types of scatter detector.

**Title: Measuring Single Cherenkov Photons**  
**Area: Particle Physics Experiment**  
**Supervisors: Prof. Franz Muheim and Dr. Stephan Eisenhardt**

The Edinburgh PPE group is involved in the LHCb experiment at the Large Hadron Collider (LHC) at CERN, which is about to start taking data. The goal of the LHCb experiment is to study the matter-antimatter asymmetry in the Universe by measuring precisely CP violating asymmetries in the decay of B mesons.

The LHCb detector will be able to perform particle identification of charged pions, kaons and protons in the momentum range of 1 to 100 GeV/c. Two Ring Imaging Cherenkov (RICH) detectors were built to determine the velocity of a charged particle traversing the detector by measuring the angle between its trajectory and the direction of the emitted Cherenkov light. The RICH detectors are equipped with Hybrid Photon Detectors (HPDs) that are capable of detecting single photons with good spatial resolution. The photo detector test facility at Edinburgh was used to measure the properties of the HPDs, including quantum efficiencies, current-voltage curves of the silicon sensors and thresholds and noise of the read-out chip which is operated at the LHC bunch crossing frequency of 40 MHz.

This project would involve measuring the properties of a novel photo detector, the flat-panel photomultiplier tube (FP-PMT) comprising 16x16 channels, which we are investigating for operation at the very high LHC luminosities that will be available in a few years. Possible topics are to measure the quantum efficiency of the FP-PMT, to investigate the channel-by-channel variations of the signal size of a FP-PMT or to improve the data acquisition system by automating the steering of the optical stages. This project will provide an opportunity to both, collecting and analysing of data and to get involved in the tools that are used in the design, development and construction of a new particle physics detector.

**References:**

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- 2) A. Augusto Alves et al., [LHCb Collaboration]  
The LHCb Detector at the LHC,  
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- 3) F. Muheim,  
LHCb upgrade plans,  
Nucl.Phys.Proc.Suppl.170:317-322,2007.
- 4) E. Albrecht *et al*  
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in a prototype RICH detector, Nucl.Instrum.Meth.A488:110-130,2002  
<http://www.ph.ed.ac.uk/particle/Exp/LHCb/notes/nimpaper.pdf>
- 5) The PPE group's LHCb webpage:  
<http://www.ph.ed.ac.uk/particle-physics-experiment/research/LHCb/>

**Title: CP Violation with Bs Mesons Decays at the LHCb Experiment**  
**Area: Particle Physics Experiment**  
**Supervisors: Prof. Franz Muheim and Prof. Steve Playfer**

The Edinburgh PPE group is involved in the LHCb experiment at the Large Hadron Collider (LHC) at CERN, which is about to start taking data. The goal of the LHCb experiment is to study the matter-antimatter asymmetry in the Universe by measuring precisely CP violating asymmetries in decays of B mesons. The results can be compared with the predictions of the Standard Model of particle physics. Deviations from the predictions would signal the existence of new fundamental interactions and particles beyond the Standard Model.

The LHC accelerator and the LHCb detector are about to start taking data. A first run is scheduled from autumn 2009 until the end of 2010. The group is particularly interested in the mixing and decay of the  $B_s$  meson, including the decays  $B_s \rightarrow J/\psi\phi$  and  $B_s \rightarrow \phi\phi$ . These modes are ideal for exploring new physics models like Supersymmetry. In the Standard Model in  $b \rightarrow s$  quark transitions are suppressed since flavour changing neutral currents are governed by quantum loop diagrams. Thus heavy particles like gluinos and squarks would make measurable contributions to these quantum loops. An observation of sizable CP violation in  $B_s \rightarrow J/\psi\phi$  would  $B_s \rightarrow \phi\phi$  be a clear discovery of new physics beyond the Standard Model.

The project would involve using the LHCb software to select the decays of interest. Monte Carlo techniques allow us to emulate the actual experiment by first generating events, which are expected to occur according to theory and then simulating their passage through materials and the signals they produce in detectors. Subsequently, these events are reconstructed as if they were data. This allows us to determine the efficiency of the LHCb detector for finding a particular decay mode. A fitting package will be used to study the sensitivity of selected events. This would involve learning the technique of doing a maximum likelihood fit and understanding the results that come from such a fitter. This is the most powerful way to find a small signal in a large noisy background with use in many other areas.

The project will provide a very good opportunity to get involved in state of the art particle physics analysis techniques. The project will require using the computer programming language C++, which is very similar to Java.

**Reference:**

- 1) The LHCb webpages: <http://lhcb.web.cern.ch/lhcb> and <http://lhcb-comp.web.cern.ch/lhcb-comp>
- 2) P. Clarke, C. Mclean, A. Osorio-Oliveros, Sensitivity studies to  $\beta_s$  and  $\Delta\Gamma_s$  using the full  $B_s \rightarrow J/\psi\phi$  angular analysis at LHCb, LHCb public note CERN-LHCb-2007-101.
- 3) Sandra Amato, Bruno Souza de Paula (Rio de Janeiro Federal U.), Judith McCarron, Franz Muheim, Yuehong Xie (Edinburgh U.), LHCb's sensitivity to new CP-violating phases in the decay  $B_s \rightarrow \phi\phi$ , CERN-LHCb-2007-047, May 2007. 21pp.
- 4) R. Antunes Nobrega et al., Status of the LHCb Detector Reoptimisation CERN/LHCC 2003-003
- 5) The PPE group's LHCb webpage: <http://www.ph.ed.ac.uk/particle-physics-experiment/research/LHCb/>

**Title: Neutrino Factory Design**  
**Area: Particle Physics Experiment**  
**Supervisor: Prof. F Muheim**

Particle accelerators have been the centre piece of particle physics research for the past half-century, and are still the only way to study particles in a well controlled manner. Studies are underway to see if the acceleration of muons is feasible.

One of the main difficulties with a muon accelerator is to produce a beam of muons in which the particles are contained in sufficiently small bunches to allow them to be manipulated, accelerated and collide before they decay. Developing a neutrino factory is a first step towards a muon collider. A neutrino factory is made by producing a beam of muons circulating in a 'storage ring'. The ring is built with several straight sections and the muons which decay along these directions will produce a beam of neutrinos. These can be fired across the earth to do neutrino oscillation experiments.

In the project, you will simulate a muon beamline at the ISIS accelerator at the Rutherford Appleton Laboratory (18 miles south of Oxford) which is planned to be extended for developing and testing a 'cooling channel' for a neutrino factory (cooling means reducing the phase space of small bunches of in the beam). The simulation will use transformation matrices to represent the changes which are made to the bunches as they traverse a range of accelerator components (dipole bending magnets, quadrupole focussing magnets, etc.).

This project will be a close collaboration with people at RAL, with the student being sent to RAL for short periods. Existing computer code is available as a basis for this work, and the project will require knowing (or learning) computer programming in C++.

The aims of the project are:

- 1) To understand how the different beam elements (dipoles, quadrupoles etc.) affect the characteristics of the beam (i.e. the change in beam size and particle direction distribution)
- 2) To improve the calculation of the characteristics of the ISIS muon beam as a function of the incoming beam from the accelerator and the magnet current settings.

**Reference: Here are some Web links:**

- 1) A directory with some files about the muon test facility at RAL  
[http://hepunix.rl.ac.uk/\\$\sim\\$edgedcock/muons/test-beam](http://hepunix.rl.ac.uk/$\sim$edgedcock/muons/test-beam)
- 2) Another muon facility at ISIS  
<http://riken.nd.rl.ac.uk/>
- 3) ISIS <http://www.isis.rl.ac.uk/>
- 4) A page of detailed links about muon storage rings  
<http://muonstoragerings.cern.ch>
- 5) A commercial beam simulation package (<http://www.dehnel.com/>)

**A catalogue of recommended reading.**

- 6) D. A. Edwards and M. J. Syphers, "An introduction to the physics of high energy accelerators", John Wiley & Sons, 1993 (very good)
- 7) P.J. Bryant and K. Johnsen, "The principles of circular accelerators and storage rings", Cambridge University Press 1993 (very good)
- 8) H. Wiedemann, "Particle accelerator physics", Springer-Verlag 1993 (very good, contains something about beam bunchers)
- 9) M. Reiser, 'Theory and design of charged particle beams', John Wiley & Sons, 1994 (also very good).

**Title: Colliding Partons at the LHC**  
**Area: Particle Physics Theory**  
**Supervisor: Prof. R.D. Ball**

Precise predictions for LHC cross-sections are an essential part of the discovery of new physics: if we cannot understand Standard Model physics at the LHC, we will not be able to see the Higgs if and when it appears. However while the LHC is a proton-proton collider, the real physics is determined by collision of the partons (quarks and gluons) inside the proton. Thus to predict LHC cross-sections, a thorough understanding of the probability distribution of the partons within the proton is essential.

Parton distribution functions (PDFs) may be determined by comparing QCD predictions for a wide variety of deep inelastic and hadronic processes with data from a range of experiments at CERN, DESY and Fermilab. Ensembles of such PDFs have been determined by the NNPDF Collaboration. They may be used to compute LHC cross-sections for a wide variety of processes using programmes like MCFM, and these results may in turn be used to estimate the impact of LHC data on the PDFs themselves.

This project aims to familiarise the student with these ideas and tools, and if carried far enough may actually involve the analysis of Tevatron data and LHC pseudodata. The project would proceed in several steps:

- (i) understanding the NNPDF partons, and how to use them, through a simple calculation of their moments, and possible comparison to lattice simulations.
- (ii) understanding how to use the MCFM code, using it to develop predictions for certain Tevatron and LHC processes (to be decided).
- (iii) comparing these predictions with real data from the Tevatron, or pseudodata for LHC experiments, and thereby estimating the impact of such measurements on the parton distributions themselves.

Perhaps even (given the time scale) we may be able to use real LHC data!

**Prerequisites:** Relativistic Quantum Field Theory, Modern Quantum Field Theory, The Standard Model, Particle Physics. Some programming experience is also essential.

**References:**

- 1) M.E.Peskin and D.V. Schroeder, An Introduction to Quantum Field Theory.
- 2) R.K. Ellis, W.J. Stirling and B.R. Webber, QCD and Collider Physics.
- 3) J.M Campbell and R.K. Ellis, MCFM (<http://mcfm.fnal.gov/>).

**Title: Quantum Theory on a Computer**  
**Area: Particle Physics Theory**  
**Supervisors: Dr. R. Horsley and Dr. B. Pendleton**

Quantum mechanics and Quantum field theory can be described in several different ways: wave mechanics, operator formalism and path integrals. The latter method, due to Feynman, when analytically continued to imaginary time becomes a partition function and is particularly suitable for numerical simulations using statistical Monte Carlo methods. (These techniques are nowadays a much used technique for simulating Quantum Chromodynamics.)

The aim of this project is for the student to understand the basic mathematics behind path integrals and Markov methods and how Monte Carlo methods (such as Metropolis and HMC) can be applied to find correlation functions. An essential part of the project is to write a programme (in a language of his/her choice) to first numerically simulate the one-dimensional harmonic oscillator (for low energy states and wavefunctions). Possible second stages might include:

- The anharmonic oscillator, instantons and supersymmetry;
- Simulation of the hydrogen atom, paying due attention to the singular nature of the potential;
- Study of 'triviality' in scalar field theory and its relation to the mass of the Higgs boson;
- Monte Carlo simulation of simple gauge theories.

Recommended prerequisites are attendance at the Quantum Theory course and knowledge of a programming language.

**References:**

- 1) M. Creutz and B. Freedman, A Statistical Approach to Quantum Mechanics, Annals of Physics, 132 (1981) 427.
- 2) R. MacKenzie, Path Integral Methods and Applications, arXiv:quant-ph/0004090.
- 3) I. Montvay and G. Munster, Quantum Fields on a Lattice, Cambridge University Press (1993), chapters 1,2,3,7.
- 4) S. Catterall and E. Gregory, A lattice path integral for supersymmetric quantum mechanics, Phys. Lett. B487 (2000) 349, [arXiv:hep-lat/0006013]; S. Catterall and E. Karamov, Testing a Fourier Accelerated Hybrid Monte Carlo algorithm, Phys. Lett. B528 (2002) 301, [arXiv:hep-lat/0112025].
- 5) T. Schafer, Instantons and Monte Carlo Methods in Quantum Mechanics, arXiv:hep-lat/0411010.
- 6) D. Bai, Multigrid solution of a path integral formulation for the hydrogen atom, arXiv:quant-ph/0405104.

**Title: Nonperturbative improvement of three-flavour clover fermions**  
**Area: Particle Physics Theory**  
**Supervisors: Dr. R. Horsley and Dr. J. M. Zanotti**

Lattice methods allow, in principle, an ab initio calculation of the fundamental parameters of Quantum Chromodynamics, QCD, together with the hadron mass spectrum and various matrix elements, [1,2,3,4]. Simulations of lattice QCD (using Monte Carlo methods) are greatly helped by the use of improved actions and operators. In this project we shall consider a three quark action (mass degenerate 'up' and 'down' quarks together with a 'strange' quark) from which we wish to remove the  $O(a)$  discretisation error (where 'a' is the lattice spacing). There is a well known technique the 'Schrodinger Functional', method which allows this.

The first background aim of this project is for the student to obtain a working knowledge of the basic mathematics behind QCD, lattice gauge theories, path integrals, Markov methods and how they can be applied to find correlation functions. The main part of the project is however numerical and consists in determining the coefficient of the 'clover'-term in the action. Basic programmes exist, but the student would be expected to spend much of his/her time running these programmes and then writing his/her own analysis programme to determine appropriate parameter regions. These would be a complementary results to [5] (which forms the basis for this project) and would allow for comparisons.

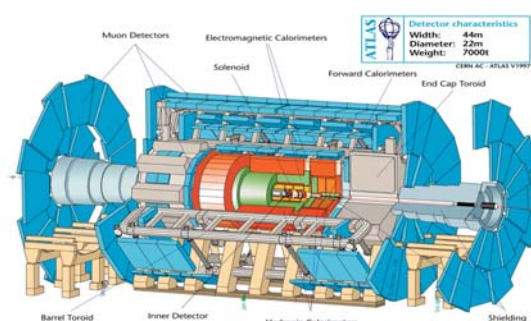
Recommended prerequisites are attendance at the Quantum Theory course and a strong interest in computing and numerical methods.

- [1] I. Montvay and G. Munster,  
Quantum Fields on a Lattice, CUP (1993), chapters 1,3,7.
- [2] J. Smit,  
Introduction to Quantum Field on a Lattice,  
CUP (2002), chapters 2,4,6.
- [3] C. Gattringer and C. B. Lang,  
Quantum Chromodynamics on the Lattice,  
Springer (2010), chapters 1--6, 8,9.
- [4] M. Luscher,  
Advanced Lattice QCD, lectures given at the Les Houches Summer School  
'Probing the Standard Model of Particle Interactions', 1997),arXiv:hep-lat/9802029.
- [5] N. Cundy, M. Gockeler, R. Horsley, T. Kaltenbrunner, A. D. Kennedy, Y. Nakamura,  
H. Perlt, D. Pleiter, P. E. L. Rakow, A. Schafer, G. Schierholz, A. Schiller, H. Stuben  
and J. M. Zanotti,  
Non-perturbative improvement of stout-smearred three flavour clover fermions,  
Phys. Rev. D79, 094507 (2009) [arXiv:0901.3302].

**Title: LHC and Higgs physics with the ATLAS experiment**  
**Area: Particle Physics**  
**Supervisors: Dr. Phil Clark and Dr. Victoria Martin**

The LHC (Large Hadron Collider) at CERN in Geneva, Switzerland, will endeavour to address many of the outstanding questions in particle and particle-astrophysics: Where does mass come from? Is there a Higgs boson? What really is dark matter? Does supersymmetry exist? Are there other exotic particles? Why does matter exist today: why wasn't it annihilated by antimatter in the early universe?

By colliding protons at centre-of-mass energies between 7 and 14TeV, the LHC recreates the energetic conditions just after the big bang. This is a unique time to study particle physics as the LHC produced its first collisions last November, after 15 years of design and construction.



ATLAS is one of the experiments located on the LHC ring, and is the largest and most complex physics detector ever built. Shown above, ATLAS consists of many layers of innovative and sophisticated subdetectors and is designed to answer as many of the above-mentioned questions as possible.

Students would have the opportunity to work as part of the ATLAS research group in Edinburgh, focussing on one of two areas:

- **Development of the ATLAS simulation program.** The simulation program simulates the response of the ATLAS detector to incident particles produced in the collisions. This project would involve monitoring data being collected by the ATLAS detector, comparing it to simulated data, and then developing the simulation program to better describe the real ATLAS data.
- **Preparation for Higgs searches.** This project will analyse both real data taken by ATLAS and simulated data. This data will be used to understand the response of the detectors to different types of physics processes and explore analysis techniques that could be used to search for Higgs boson in the ATLAS data.

Working with the ATLAS group is an excellent opportunity for training in particle physics in preparation for a future PhD in the field.

References:

- The ATLAS experiment: <http://atlas.ch>
- The ATLAS detector (2008 JINST 3 S08003) <http://jinst.sissa.it/LHC/>
- ATLAS simulation <https://twiki.cern.ch/twiki/bin/view/Atlas/AtlasSimulation>

**Title: The WMAP Cosmic Microwave Background (CMB) Spectrum**  
**Area: Cosmology / Particle Physics**  
**Supervisors: Dr. A Berera and Dr. R Horsley**

The CMB is not a perfect isotropic radiation field. Deviations from isotropy are at the level of one part in 10<sup>5</sup>. The understanding of these fluctuations has become the cornerstone of what in the last decade has become to be called precision cosmology. The Wilkinson Microwave Anisotropy Probe is a satellite currently in orbit around earth which is measuring the CMB. The first year data from this probe has revealed many detailed features about the CMB, such as the temperature power spectrum and temperature-polarization cross-power spectrum.

The aim of this project is first to understand the features of the data and the basic mathematics behind it. The student also needs to understand what implications these results have for particle cosmology, such as inflation, dark energy, dark matter and neutrino masses. The CMB spectrum is affected by physics in the early Universe, which is at very short scales involving fundamental particle physics phenomenon. At this extreme, physics at the Planck scale has been shown to influence the CMB spectrum at a possibly observable level [5]. We will attempt to constrain the WMAP data and see if signatures of these trans-Planckian effects can be found.

The student will have understand and learn to use the CMBfast computer code, which is an extensive code for computing CMB anisotropies, polarization and matter power spectrum. This will require some knowledge of linearized General Relativity perturbation theory. Finally with the CMBfast code, the student will explore a few different cosmological scenarios for the evolution of the CMB. The student should have taken General Relativity and it is recommended to have some background in particle physics.

#### **References:**

- 1) S. Dodelson, *Modern Cosmology*, Academic Press, (2003).
- 2) E. Komatsu et al., (WMAP Collaboration), *Astrophys. J. Suppl.* 180, 330 (2009) [arXiv:0803.0547 [astro-ph]]; J. Dunkley et al., (WMAP Collaboration), *Astrophys. J. Suppl.* 180, 306 (2009), [arXiv:0803.0586 [astro-ph]].
- 3) W. H. Kinney, *TASI Lectures on Inflation*, arXiv:0902.1529 [astro-ph].
- 4) J. A. Peacock, *Cosmological Physics*, Cambridge University Press, (1999).
- 5) R. Easther, et. al., *Physical Review D* 66, 023518 (2002), [arXiv:hep-th/0204129].

**Title: Models of hydrodynamic turbulence**  
**Area: Mathematical Physics**  
**Supervisor: Dr. Arjun Berera**

Turbulence is the oldest unsolved problem of classical theoretical physics. The governing equation for studying turbulence is the Navier-Stokes equation, which is nonlinear and thus insoluble. To address this problem it requires either analytic approximation techniques or direct numerical simulations (DNS).

The project involves examining some approximate models of turbulence and studying various dynamic properties of these systems. This will be approached with both analytic and numerical methods. This project will require a good knowledge of statistical mechanics and a working knowledge of either Java or C programming languages.

**Title: The Higgs mechanism beyond the Standard Model**  
**Area: Particle Physics Theory**  
**Supervisor: Dr. Einan Gardi**

The Higgs mechanism is a key element in the Standard Model of particle physics; it explains how the weak vector bosons  $W$  and  $Z$  become massive, while photons remain massless. This is the 'Electroweak symmetry breaking mechanism'.

The Higgs sector itself has not yet been explored experimentally. Its direct exploration is the primary goal of the Large Hadron Collider (LHC), which started to take data this year. It is expected that this exploration will open a window towards new physics, possibly new interactions at short-distances, which have not been observed so far.

The project will focus on analysing a specific extension of the Standard Model which includes additional vector bosons as well as an extended Higgs sector.

As a preparation the student will re-derive known results within the SM, and gain basic understanding of the idea of spontaneous symmetry breaking and the Higgs mechanism. The work on the model itself will start by analysing the Lagrangian, deriving the gauge boson masses, and determining the Feynman rules for the interactions. The final goal will be to compute, within this model, a couple of electroweak precision observables at the one-loop order.

Prerequisites: Relativistic Quantum Field Theory, Particle Physics.

**References:**

- 1) Michael E. Peskin and Daniel V. Schroeder 1995, An introduction to Quantum Field theory, Addison-Wesley.

**Title: Long-distance singularities in QCD scattering amplitudes**  
**Area: Particle Physics Theory**  
**Supervisor: Dr. Einan Gardi**

Understanding the structure of gauge theory scattering amplitudes is important from both the fundamental field-theoretic perspective, and the pragmatic one of collider physics. A salient feature of QCD amplitudes is the fact that they present long-distance singularities.

The study of infrared singularities in QCD amplitudes, which has a three-decade-long history, recently received a major boost. A set of all-order constraints on the singularity structure was derived for a general  $n$ -legged amplitude, taking the form of a set of  $n$  differential equations involving the 'cusp anomalous dimension'.

A general solution of these equations was derived under a simplifying assumption with regards to the dependence of the 'cusp anomalous dimension' on the colour representation of scattered partons (quadratic Casimir scaling). This solution is remarkably simple: it corresponds to a sum over colour-dipole interactions formed by any pair of legs. It correlates in a simple way the colour and kinematic dependence of the amplitude.

The goal of the project is to derive a solution to the same equations under a modified assumption, where a quartic Casimir shows up in the 'cusp anomalous dimension'. The solution is expected to take the form of a quadrupole interaction. As time permits, the student will also analyse the solution in the limit where two hard partons become collinear.

Prerequisites: Relativistic Quantum Field Theory, Particle Physics.

**References:**

- 1) Michael E. Peskin and Daniel V. Schroeder 1995, An introduction to Quantum Field theory, Addison-Wesley.
- 2) E. Gardi and L. Magnea, "Factorization constraints for soft anomalous dimensions in QCD scattering amplitudes," JHEP **0903** (2009) 079 [arXiv:0901.1091 [hep-ph]].

**Title: Higgs plus jet production in gluon-gluon fusion at the LHC**  
**Area: Particle Physics Theory**  
**Supervisor: Dr. Einan Gardi**

The main production channel for the Higgs boson at the Large Hadron Collider (LHC) is by gluon-gluon fusion. In this process a virtual top quark loop mediates the interaction.

In a certain fraction of the events, the Higgs is produced together with one or more energetic jets due hard gluon emissions. Interpreting the LHC data requires to perform theoretical calculations of Higgs production not only for the total cross section, but also for specific (exclusive) final states, where additional jets are produced.

In this project we will focus on the computation of two specific processes,  $gg \rightarrow H$  and  $gg \rightarrow Hg$ , the latter giving rise to Higgs plus a single jet. In each case the calculation will be done in two ways:

(1) by considering the effective Lagrangian corresponding to the limit where the top quark is assumed to be significantly heavier than the available energy.

(2) by computing explicitly the one-loop diagrams with a virtual top quark. The second approach will allow us to determine the dependence of the cross section on the top-quark mass. This calculation will involve the use of 'FORM', a specialised computer algebra package.

Prerequisites:

Relativistic Quantum Field Theory, Particle Physics.

**References:**

- 1) Michael E. Peskin and Daniel V. Schroeder 1995, An introduction to Quantum Field theory, Addison-Wesley.
- 2) FORM, by Jos Vermaseren, <http://www.nikhef.nl/~form/maindir/maindir.html>

**Title: General Relativity as an Effective Theory**  
**Area: Particle Physics Theory**  
**Supervisor: Dr. L Del Debbio**

Effective theories have become a central tool for describing the dynamics of physical systems by separating the low-energy quantum effects from the high-energy features of the theory.

This method is particularly useful to understand the low-energy dynamics of Quantum Gravity: even though we are currently unable to quantize gravity consistently, the leading quantum corrections at large distance can be computed.

The aim of this project is to understand the effective theory approach to gravity and to reproduce the results in Ref.~[2].

Prerequisites: Basics of General Relativity, Relativistic Quantum Field Theory.

**THE STUDENT SHOULD COME AND DISCUSS WITH DR DEL DEBBIO BEFORE SIGNING UP FOR THIS PROJECT**

**References:**

- 1) S. Weinberg, Gravitation and Cosmology.
- 2) J. Donoghue, gr-qc/9405057.

**Title: Numerical Simulation of Stochastic Differential Equations**  
**Area: Particle Physics Theory**  
**Supervisor: Dr. L Del Debbio**

Stochastic differential equations (SDE) are a major tool in a wide range of applications, ranging from quantum field theory, to biology, and finance.

The aim of this project is to introduce the theory of SDE through examples and numerical simulations, and develop simple algorithms for quantum field theory and financial problems.

Prerequisites: Advanced Quantum Theory, Relativistic Quantum Field Theory, computational methods (C/C++ required).

**THE STUDENT SHOULD COME AND DISCUSS WITH DR DEL DEBBIO BEFORE SIGNING UP FOR THIS PROJECT**

**References:**

- 1) D.J. Higham, SIAM Review, 43, 525, 2001.
- 2) M. Baxter, A. Rennie, Financial Calculus.
- 3) B. Oksendahl, Stochastic Differential Equations.

**Title: EIGENVALUES OF THE DIRAC OPERATOR**  
**Area: Particle Physics Theory**  
**Supervisor: Dr. L Del Debbio**

A lot of effort is currently devoted to numerical simulations of Quantum Field Theories with dynamical fermions. Simulations of QCD near the chiral limit are the primary aim of these endeavours, and require dedicated algorithms and large computers.

Quantum Field Theories in lower dimensions are an ideal playground to perform numerical simulations without the computational cost of the four-dimensional systems.

The goal of this project is to study the spectrum of eigenvalues of the Wilson-Dirac operator in two dimensions. Despite its relative simplicity, this problem has all the features of a "real" numerical simulation.

There are three stages to the project:

- 1) Dirac equation in the continuum theory, free-field solutions. Dirac equation in 2-dim. Fermions on the lattice.
- 2) Implementation of the Dirac matrix on the lattice, algorithms for computing the eigenvalue spectrum. Free-field case.
- 3) Eigenvalue spectrum.

**Prerequisites:** Advanced Quantum Theory, Relativistic Quantum Field Theory, computational skills (C/C++ required).

**THE STUDENT SHOULD COME AND DISCUSS WITH DR DEL DEBBIO BEFORE SIGNING UP FOR THIS PROJECT**

**References:**

- 1) H.J. Rothe, Lattice Gauge Theories, an Introduction.
- 2) J. Smit, Introduction to Quantum Fields on a Lattice.
- 3) Y.Saad, iterative methods for sparse systems.

**Title: Computational Group Theory**  
**Area: Mathematical Physics**  
**Supervisor: Prof. A D Kennedy**

This project follows on from a successful previous MPhys project in using diagrammatic methods ("birdtracks") to carry out group theory calculations of interest in Quantum Field Theory. This project involves

- 1) learning the techniques for calculating the matrices of irreducible representations of the symmetric group;
- 2) implementing them on a computer using Maple;
- 3) using the results to compute 3j and 6j coefficients for Lie algebras using some novel diagrammatic techniques previously developed.

**Prerequisites:** Groups & Symmetries

**Reference:**

Morton Hamermersh, *Group Theory and its Applications to Physical Problems*, Dover reprint edition, ISBN 0486661814.

**Title: Renormalization in  $\phi^3$**   
**Area: Particle Physics Theory**  
**Supervisor: Prof. A D Kennedy**

In general Quantum Field Theories are plagued by infinities when quantum corrections in terms of loop Feynman diagrams are evaluated. The theoretical framework to deal systematically with such divergences and render the theory finite is Renormalization Theory. One of the simplest models to study renormalization theory turns out to be a scalar field theory with a cubic interaction term formulated in  $d=6$  dimensions. The project should guide you through the basics of renormalization theory applied to this model. In detail the project will evolve like:

- 1) Formulation of  $\phi^3$  theory and the loop expansion.
- 2) Evaluation of all divergent one-loop diagrams using  $n$ -dimensional integral technical ("dimensional regularisation").
- 3) Renormalization of the theory at one-loop
- 4) Feynman parameter representation of two-loop diagrams and definition of two-loop counterterms.

Prerequisites: Relativistic Quantum Field Theory, Particle Physics.

PLEASE ENSURE YOU SEE PROF KENNEDY BEFORE SIGNING UP FOR THIS PROJECT

**Title:            The high-redshift cut-off of powerful radio-loud AGN**  
**Area:            Astrophysics**  
**Supervisor:    Dr. Philip Best**

Radio-loud AGN trace the locations of the most massive galaxies in the Universe. The evolution of the high redshift space density of radio-loud AGN is therefore a key measurement of the early growth of massive galaxies, and their associated massive black holes. For the last 10 to 20 years, however, there has been much debate about the presence or absence of a "redshift cut-off" - a sharp decline in the space density of radio sources beyond  $z \sim 2$  - and solving this issue is fundamental to determining the precise formation epoch of these massive systems.

To critically address this issue, we have been developing a new radio source sample, known as "CENSORS", at faint radio fluxes. These data offer the possibility for a very precise determination of the high redshift cut-off, but that result is critically dependent upon getting accurate redshift measurements or estimates for all of the sources. We have obtained spectroscopic redshifts for over 70% of the sources, but for the remainder it is now essential to use multi-wavelength photometry to derive the best redshift estimates. We have recently obtained near-infrared J and H-band images of these galaxies, to go with existing I and K-band data. The student will be responsible for reducing and analysing these new data, obtaining accurate photometry, and matching with model galaxy spectra to obtain the best redshift estimates; once this is achieved, the focus will move to analysing and quantifying the strength of the redshift cutoff.

The student will gain experience in near-infrared data reduction and analysis, modelling techniques, AGN and galaxy evolution, and radio source astrophysics.

**Title: The masses, environments and clustering properties of star-forming galaxies in the Sloan Digital Sky Survey**  
**Area: Astrophysics**  
**Supervisor: Dr. Philip Best**

It is well known that the prevalence of star-formation in galaxies in the nearby Universe is strongly dependent upon their properties - in particular their masses [massive galaxies are generally not star-forming, whilst less massive galaxies are], their morphologies [ellipticals versus spirals], and their environment [star formation is suppressed in galaxy clusters]. This project is designed to convert these qualitative statements into accurate quantitative measurements. This is crucial because our on-going 'Hi-z Emission Line Survey' (HiZELS), is making quantitative measurements of these properties at redshifts between 0.8 and 2.5, and an accurate low redshift baseline determined in exactly the same manner is required to fully interpret these results.

The project will use data from the Sloan Digital Sky Survey, which is a spectroscopic survey of nearly a quarter of the entire sky, providing redshifts and spectral measurements for around a quarter of a million galaxies with a median redshift  $z \sim 0.1$ . The student will begin by extracting a robust sample of star forming galaxies from this survey, using the same technique as is used for HiZELS, namely the H-alpha emission line. Masses and environments of these star forming galaxies will be measured and characterised, as will the clustering properties of the galaxies. The results obtained will be directly compared with the higher redshift HiZELS results to determine the nature of the evolution of the population.

The student will gain experience in handling and analysing large astronomical datasets, in detailed studies of starforming galaxies, and in the underlying astrophysics of galaxy formation and evolution.

**Title: Self-gravitating discs in active galactic nuclei**  
**Area: Astrophysics**  
**Supervisor: Dr. Ken Rice and Prof. Andy Lawrence**

The evolution of accretion discs that are massive enough for their own self-gravity to be important is now quite well understood. A lot of work in this area has, however, focused on the evolution of such discs around young, newly forming stars, with the primary goals of understanding the transport of angular momentum and if such discs can fragment to form substellar - or planetary mass - companions. In this project you will extend this work to consider how self-gravity influences the evolution of discs around supermassive black holes in active galaxies. One of the goals of the project will be to self-consistently determine the properties of such discs accreting at the Eddington limit and how the accretion rate varies with time. An additional goal will be to establish the radial range over which we might expect such discs to fragment to form stellar companions. This process might help to explain the presence of a population of massive stars orbiting the supermassive black hole in our own galactic centre. The project will be mainly computational and, although much of the code is already developed, some development and testing will be required

**Title:** Exploring the Andies: A Near-Infrared Look at Andromeda's Dwarf Spheroidal Galaxy Population  
**Area:** Astrophysics  
**Supervisor:** Dr. Annette Ferguson

Dwarf spheroidal (dSph) galaxies are the tiniest but most numerous members of the galaxy population in the Universe. Because of their extremely low luminosities and surface brightnesses, most of what we currently know about dSph galaxies comes from studying those systems which lie in the immediate vicinity of the Milky Way. The picture that has emerged from this work is that dSph galaxies are composed of ancient stellar populations, with very few new stars having formed over the last 10 Gyr (i.e. since a redshift of 2).

To test the universality of this result, we have conducted a comprehensive near-infrared imaging survey of the dSph population around our nearest large neighbour, the Andromeda galaxy. For thirteen of the 'Andies', we have in hand fully-reduced wide-field images in the JHK passbands. The project will involve using these data to search for and quantify the presence of luminous red sources in these galaxies, which are likely to be intermediate-age ( $\approx$  3-8 Gyr) asymptotic giant branch stars. The spatial distributions and luminosity functions of the stars will be computed and compared to the predictions of theoretical population synthesis models (accessible through a web-interface) to place estimates on the amount of star formation that could have taken place at intermediate epochs. Ultimately, these results can be compared to those found for the Milky Way dSphs.

In addition to studying the Andromeda dSph galaxy population, the data can also be used to search for asymptotic giant branch stars in the extended regions of Andromeda's stellar halo as well as for studies of foreground Milky Way main sequence stars.

The project will involve developing significant expertise in the evolution of stars and dwarf galaxies. It will require manipulating photometric datasets and writing some analysis code (preferably in IDL).

**Title: Finding the largest galaxies in the low-redshift Universe**  
**Area: Extragalactic astrophysics**  
**Supervisor: Dr. Bob Mann**

The largest galaxies are those belonging to a class called cD galaxies. These are very massive elliptical galaxies, usually found in the centres of galaxy clusters, and distinguished from ordinary cluster ellipticals both by their greater size, mass and luminosity and by their possessing a large stellar envelope or halo - i.e. an excess of stars in the outer regions of the cD compared with the near-universal radial intensity profile exhibited by normal ellipticals.

The stars in the stellar envelopes of cD galaxies are often thought to belong more to the cluster as a whole than to the cD galaxy itself, but no clear explanation exists for the origin of the halo or of its relationship to the overall properties of the cluster. In large part, this is due to the way that studies of cD galaxies usually start with a cluster catalogue, so that existing samples of cD galaxies exhibit selection biases associated with the way that their parent cluster samples were defined.

This project is the first attempt to create a catalogue of cD galaxies on the basis of their defining quality - i.e. possession of a stellar envelope - rather than as a by-product of cluster survey. It will make use of data from the SuperCOSMOS Sky Survey (SSS), an all-sky photographic survey of the local Universe undertaken by the University's Wide Field Astronomy Unit.

The project will involve the querying and extraction of data from online databases and the writing of analysis code, and will enhance transferable IT skills as well as developing a knowledge of the astrophysical properties of cD galaxies.

**Title: Tracing the evolution of the black-hole: bulge relation**  
**Area: Extragalactic Astrophysics**  
**Supervisor: Dr. Ross McLure**

The discovery that every massive local galaxy harbours a supermassive black hole with a mass proportional to the surrounding galaxy has dramatic implications for models of galaxy formation. The existence of this black-hole: galaxy relationship immediately implies that starformation and black-hole growth are intimately related, and that every massive galaxy must have been an active quasar at some point in its history. However, in order to constrain different models of galaxy: black-hole co-evolution, it is necessary to constrain how the black-hole: galaxy relationship evolves as a function of cosmic time. The aim of this project is to constrain what the black-hole: galaxy mass ratio was 8 billion years ago by analysing deep, high resolution, near-infrared images of a sample luminous quasars at redshift one. The key to this project is that quasars are the only high-redshift objects for which it is possible to measure both their galaxy mass (near-IR luminosity) and their black-hole mass (optical emission lines). This project will provide valuable hands-on experience of near-IR data reduction, two-dimensional modelling of imaging data and the analysis of optical spectra.

**Title: The evolution and nature of Lyman break galaxies at redshift  $z > 3$**   
**Area: Extragalactic Astrophysics**  
**Supervisor: Dr. Ross McLure**

One of the key questions in observational cosmology is delineating the evolutionary link between the galaxies we observe in the local Universe and the wide variety of different types of high-redshift galaxies. One population of high-redshift galaxies which has been studied intensively in recent years is the so-called Lyman break galaxies (LBGs), which display a strong discontinuity, or "break", in their spectra due to neutral hydrogen absorbing their light at wavelengths short-ward of 912 Angstroms (The Lyman limit). As a consequence, LBGs at different redshifts can be readily identified from deep imaging, due to their red colour in filters sampling wavelengths either side of 912 Angstroms. The aim of this project is to apply the Lyman break selection technique to a unique, multi-wavelength data-set called the UKIDSS Ultra-deep Survey (UDS). The UDS covers a square degree on the sky, and consists of deep imaging spanning the UV, optical, near-infrared and mid-infrared wavelength regimes. In the first instance this data-set will allow you to identify samples of LBGs at redshifts  $z=3$ ,  $z=4$  and  $z=5$  (when the Universe was only 1-2 Gyrs old) and to investigate how their luminosity function evolves over this time interval. Latterly, the unique multi-wavelength data-set available in the UDS will allow you to study the stellar masses and starformation rates of high-redshift LBGs, and to investigate how LBGs are related to other high-redshift galaxy populations.

**Title: Galaxy formation in the multiverse**  
**Area: Cosmology**  
**Supervisor: Prof. J A Peacock**

A fundamental difficulty in cosmology is understanding how the vacuum density can take a non-zero figure that is so low compared to a natural particle-physics scale. An increasingly popular explanation is the "anthropic" or "multiverse" solution, in which the existence of an ensemble of universes is postulated: those with extreme values of the vacuum density are expected to have trouble forming galaxies, and so are less likely to be experienced by observers. To implement this calculation, it is necessary to predict the amount of star formation that occurs over all time in a given member of the multiverse, and so far this has been done in an extremely crude way, based simply on the fraction of mass in the universe that collapses into a system of mass similar to the local group. Varying the vacuum energy will change the physical timescales of structure formation, and so alter the efficiency of galaxy formation. The intention of this project is to use GALFORM, which is the leading code for calculating the processes of galaxy formation, to compare with the simple models. The initial challenge is to run the code into the far future to see how many stars ever form, and then to vary cosmology to see how this responds to changes in the vacuum density, or other critical physical parameters which may vary between members of the multiverse. Some thought will need to be given to assumptions in GALFORM that may not be appropriate for very large times in the future.

The project would give an introduction to some of the forefront issues in the fundamental nature of the universe, as well as an overview of the physical mechanisms involved in galaxy formation. Reasonable computational skills will be required. For some background reading, see:

<http://arxiv.org/abs/0705.0898> <http://arxiv.org/abs/astro-ph/0511338>  
<http://arxiv.org/abs/astro-ph/0605045>

**Title:            Discovering the Epoch of Reionisation**  
**Area:            Cosmology**  
**Supervisor:   Prof. Avery Meiksin**

According to the Big Bang theory, all the baryonic material (hydrogen and helium) in the universe first materialised as a hot ionised gas. Around a redshift of  $z = 1000$ , when the universe was 300,000 years old, the baryons recombined at a time known as the Recombination Era. Measurements of the Cosmic Microwave Background, however, show that in fact the gas is highly ionised, and must have been so since  $z = 8$ . The history of the Universe between  $z = 1000$  and  $z = 8$ , when the hydrogen was re-ionised, is mostly unknown. New radio telescopes like LOFAR ([www.lofar.org](http://www.lofar.org)) and the Square Kilometre Array (SKA) ([www.skatelescope.org](http://www.skatelescope.org)) have been designed to detect this Epoch of Reionisation, one of the paramount challenges of modern cosmology. The detection relies on measuring the 21cm signature from the neutral hydrogen illuminated by the first radiating objects believed to form in the Universe.

The purpose of this project is to use cosmological simulations of the hydrogen gas and dark matter to predict the radio signature LOFAR and SKA should detect. The student will be part of a group involved in cosmological structure simulations at the Edinburgh Centre for Computational Astrophysics ([www.roe.ac.uk/~aam/ecca/Research/igm/background.html](http://www.roe.ac.uk/~aam/ecca/Research/igm/background.html)).

The project will introduce the student to numerical methods in cosmology and the physics of cosmological structure formation.

Strong programming skills are required. Much of the project will be carried out using the programming language IDL for visualisation, for which the student will receive guidance.

References:

1. <http://www.roe.ac.uk/~aam/ecca/Research/igm/background.html>
2. Meiksin, A. "The Physics of the Intergalactic Medium" (<http://ads.nao.ac.jp/abs/2007arXiv0711.3358M>)

**Title: Galaxy-shear correlations in cosmology**  
**Area: Cosmology**  
**Supervisor: Prof. Alan Heavens**

Weak gravitational lensing is a powerful tool for cosmology, and has considerable promise for studying Dark Energy and deviations from Einstein gravity. Light bending by density fluctuations along the line of sight lead to correlations of the shapes of galaxy images, a process called Cosmic Shear. A potentially very important source of error arises if foreground galaxy orientations are correlated with background image orientations, and this phenomenon is expected to exist at some level. This project will study the problem theoretically, using perturbation theory. It would suit a student with a strong mathematical background, and who has studied Astrophysical Cosmology. Some significant programming would also be involved.

**Title: Planet finding with advanced statistical techniques**  
**Area: Cosmology**  
**Supervisor: Prof. Alan Heavens**

Planets passing in front of their parent stars cause a periodic dip in the amount of light received on Earth. Finding these small changes in a noisy datastream is a big challenge, and is computationally very expensive. This project will apply a massive data compression technique to attempt to find planets efficiently in a large dataset of light curves from stars monitored with SuperWASP. This method has not been tried on real data to date, and there is a possibility of finding new systems. The project has a large computational element, and would also involve understanding the statistical methods employed.

**Title: Existence of Extended Dark Matter Halos around Bright Isolated Galaxies**  
**Area: Cosmology**  
**Supervisor: Dr. Peder Norberg**

The view that galaxies are surrounded by large dark matter halos dates back more than 30 years to the pioneering study of the rotation curve of M31 by Rubin & Ford (1970). Extended galactic halos are, in fact, a generic feature of the cold dark matter model of galaxy formation (Blumenthal et al. 1984), but this fundamental theoretical prediction has limited direct observational support, especially for galactic halos. Only since the advent of large galaxy survey is it possible to address this prediction in a statistical way.

Using SDSS DR6, the largest galaxy redshift survey to date with over 600'000 galaxy redshifts over  $\sim 1/5$  of the sky, and GAMA, a currently on-going galaxy redshift survey probing even fainter galaxies than SDSS, we propose to identify a large sample of isolated bright galaxies, together with their much fainter satellites. We will test, by applying the same isolation criteria to realistic mock galaxy catalogues constructed for the GAMA survey from the Millennium simulation, the hypothesis of stacking satellites of isolated galaxies of similar luminosity for measuring the underlying velocity dispersion. By using a likelihood estimator, which accounts for interlopers in the satellite samples, our aim is to estimate, as function of projected radius and primary galaxy type, the associated satellite velocity dispersion. Depending on the quality of the mock catalogues (ie. in their capacity of reproducing the data, so that a proper interpretation can be made), an attempt to estimate the dynamical mass of the observed halos will be made.

The direct focus of the project is to work mainly with real data (SDSS & GAMA) and measure the underlying halo masses, with an estimator calibrated on mock galaxy catalogues. With his project, the student will familiarize him/her-self with the mock galaxy catalogues constructed from large N-body simulations, get use to handle large galaxy catalogues (both real and mock) and learn about biases and limitations of real and mock galaxy surveys.

This project falls in the category: statistical; theoretical; computational. Note that programming skills in Fortran or C is very useful.

Further information:

GAMA: <http://www.eso.org/~jliske/gama/>

SDSS: <http://www.sdss.org/dr6/index.html>

Mocks: <http://www.mpa-garching.mpg.de/millennium/>

**Title: Comparative study of photometric redshift estimators**  
**Area: Cosmology**  
**Supervisor: Dr. Peder Norberg**

In recent years, special effort has been devoted to the development of robust and reliable photometric redshift estimators, hereafter referred as photo-z estimators. The main science aims behind this effort are either to obtain in a "cheap" way statistical redshifts for large multi-band imaging surveys or to derive physical galaxy properties (like stellar masses, etc.) for multi-wavelengths samples that would be too costly to get spectra for. For that reason, two families of photometric redshift estimators have been developed: artificial neural network (e.g. ANNz) and template spectral energy distribution (SED) fitting (e.g. Hyperz) based ones. The former require a training set to be set up, while the latter requires a realistic set of SED templates to work properly.

For this project, those types of publicly available codes will be tested using SDSS data, for which quality redshift information is available down to  $r \sim 17.7$  together with rather accurate photometry. We will investigate the statistical properties of the photo-z distributions, with particular attention to the individually inferred photo-z distributions, their sensitivity to catastrophic photometric redshift failures and the robustness of the results for different galaxy samples.

The real test for the photometric redshift codes will come when the analysis is extended to fainter objects in SDSS, for which the GAMA galaxy redshift survey is currently collecting a "complete" redshift sample. The aim here is to see how much results calibrated on a brighter sub-sample can be extended to fainter galaxy samples. The work done during the course of the project is fundamental for upcoming detailed clustering studies that will be performed with large imaging surveys like Pan-STARRS, for which only limited spectroscopic information will be available.

This project falls in the category: statistical; theoretical; computational. Note that programming skills in Fortran or C is very useful.

Further information:

ANNz: <http://zuserver2.star.ucl.ac.uk/~lahav/annz.html>

Hyperz: <http://webast.ast.obs-mip.fr/hyperz/>

**Title: Environmental study using GAMA and SDSS**  
**Area: Cosmology**  
**Supervisor: Dr. Peder Norberg**

GAMA, the Galaxy And Mass Assembly survey, is a novel galaxy redshift survey that is unique by its size and depth. Only GAMA is able to provide over a statistically representative volume spectra of galaxies as faint as the Small Magellanic Cloud (and even fainter). This 150 square degree redshift survey of the 'local' Universe has been designed to answer many essential questions relative to galaxy formation.

One of them is the influence of the large scale environment on the galaxy population. Preliminary studies with SDSS and 2dFGRS, the largest redshift surveys of the 'local' Universe to date, have allowed us to measure in great detail the environmental dependence of the galaxy luminosity function. However, those studies were limited by the depth of the surveys. As GAMA reaches typically ten times deeper than SDSS, it is natural to attempt to re-address those findings. Because GAMA is not as large as neither SDSS or 2dFGRS, it will become important to use both GAMA and SDSS jointly in this analysis.

This project has two basic goals: first design a simple method that can measure quantitatively in a robust fashion the large scale environment of a galaxy, applicable to both real data (GAMA & SDSS) and mock/simulated data; then the aim is to study the galaxy luminosity function as function of colour and environment, and critically compare models with real data.

With this project, the student will familiarize him/her-self with the mock galaxy catalogues constructed from large N-body simulations, get use to handle large galaxy catalogues (both real and mock) and learn about biases and limitations of real and mock galaxy surveys.

This project falls in the category: statistical; theoretical; computational. Note that programming skills in Fortran or C is very useful.

**Further information:**

GAMA: <http://www.eso.org/~jliske/gama/>

SDSS: <http://www.sdss.org/dr6/index.html>

Mocks: <http://www.mpa-garching.mpg.de/millennium/>

**Title:           The evolution of general cosmological perturbations**  
**Area:           Cosmology**  
**Supervisor:   Prof. Andy Taylor**

Many areas of cosmology require a detailed understanding of the linear evolution of cosmological perturbations in the Universe: the interpretation of the Cosmic Microwave Background, Galaxy Redshift Surveys and large-area Gravitational Lensing surveys. The linear theory of the evolution of cosmological perturbations in the Early Universe is now quite advanced, combining elements of general relativity, fluid mechanics and radiation transfer. Given a set of initial conditions, cosmological perturbations can be evolved forwards in time, through matter-radiation equality and recombination, using publicly available codes such as CMBfast.

However, these codes are not regularly updated to keep track of the latest developments in Cosmology, nor are they simple enough to allow straightforward generalization. In addition, although fast, these calculations must be made faster to allow the generation of the matter power spectrum and CMB power spectrum to be made “on the fly” when estimating cosmological parameters.

This project is to develop a simpler numerical code to evolve the most general initial conditions in the Early Universe until post-recombination, and to study different initial conditions, such as curvature and isocurvature modes, the effects of extra dimensions such as in the string/M-theory braneworld model, and testing different models for the dark energy. These predictions can be tested against data from the CMB and large-scale structure. "The student should have some knowledge of computing, preferably in Fortran, IDL or Matlab."

**Reference:**

<http://www.cmbfast.org/>

**Title: A Search for Dark Halos in the Millennium Simulation**  
**Area: Astrophysics (Computational Cosmology)**  
**Supervisor: Dr. Eric Tittley**

Galaxy clusters are the largest virialised structures in the universe. Their gravitational fields accumulate matter over large volumes and hence should have dark matter and gas in proportions closely matching the universal average. Recently, galaxy clusters have been observed that have unusual proportions of dark matter and gas. Those that are missing gas are referred to as dark halos. Some anomalies are likely due to ongoing mergers, eg the Bullet Cluster, but others are more enigmatic.

In this project, the student will search the data set from the Millennium Simulation with Gas for clusters with anomalous gas fractions. This will require generating a new catalogue of halos, selected by dark matter only and by gas only. A comparison will give statistics on the probability of a cluster having a particular baryon fraction.

The student will use their knowledge of programming to create codes to process the data. The Millennium Simulation with Gas is a large dataset (65Gb) so experience will be gained in dealing with large datasets.

Experience will also be gained in cosmology and high-performance computing

**Title:            Implement Polar Gridding in the Hydrodynamical Radiative  
Transfer Code, EnzoRT**  
**Area:            Astrophysics (Computational Cosmology)**  
**Supervisor:    Dr. Eric Tittley**

When it was about one billion years old, the universe underwent a phase change in which the primary phase of baryonic matter went from neutral gas to ionised plasma. The phase change impacted subsequent star and galaxy formation. The details of when and how the phase change occurred are not known. At the University of Edinburgh, we have developed a Radiative Transfer (RT) code for modelling the ionisation of the early universe by the first stars, galaxies, and quasars. Recently, the RT code has been merged with a cosmological hydrodynamic code, Enzo, which simulates the dark matter and gas evolution. Currently the radiative transfer can only be computed for plane waves crossing the simulated volume of the universe. More useful would be to propagate the radiation spherically, as it would around a real source.

In this project, the student will develop a method to grid the Enzo gas data onto a polar grid to be passed to the RT component.

The student will use their knowledge of programming (C, C++) and numerical methods.

Experience will be gained in cosmology and high-performance computing.

**Title: FPGA Hardware Adapted for a Radiative Transfer Code**  
**Area: Astrophysics (Computational Cosmology)**  
**Supervisor: Dr. Eric Tittley**

Radiative Transfer (RT) codes are used to simulate a variety of astrophysical problems, from stellar atmospheres and star formation to reionisation in the early universe by the first stars, galaxies, and quasars. Modern RT codes such as those developed at the University of Edinburgh are computationally expensive and require many thousands of hours on high performance computers. At the core of our RT code is a set of integrals which consume >95% of the computational time.

A Field Programmable Gate Array (FPGA) is a computer chip containing programmable logic circuits. The logic circuits can be programmed to perform a single task in a highly efficient manner, many times faster than a traditional processor. In this project, the student will adapt a RT code to use FPGA hardware, focusing on the internal integral routine.

The student will be using their knowledge of programming (C) and computer hardware in a project in cutting-edge computer science. Knowledge of numerical methods would be beneficial. Experience will be gained in cosmology and high-performance computing

**Title: Automated classification of near infrared variables in large synoptic surveys**  
**Area: Astronomy**  
**Supervisor: Dr. Nicholas Cross**

Astronomy has entered a new era of wide field time variability surveys, with ambitious all sky surveys such as Pan-STARRS about to start and LSST being planned. Given the amount of data generated by these surveys, it is essential that data archives can provide robust variability classifications that allow astronomers to pick out useful subsamples efficiently.

The Wide-Field Astronomy Unit at the Institute for Astronomy is currently archiving data from UKIRT WFCAM, the current fastest near infrared survey instrument and will start archiving data from the VISTA telescope in early 2009. These will be the largest near infrared surveys for some time. The VISTA Variable survey starting in 2009 will be the first large near infra red survey of variable stars and will eventually observe of ~1 billion stars as it covers the galactic plane and bulge. The main science goal is to find and identify RR-Lyrae stars to estimate accurate distances to structures in the bulge. This survey will start too late to be used for the current project, but there are several smaller synoptic datasets taken by WFCAM already, which can be used to develop a suitable tool.

The task of the student will be to use the available data: colours, statistical measurements of variability, star-galaxy separation etc to find and classify variable objects and demonstrate that these classifications are useful astronomically and robust enough to work on different surveys. The work of this project may be incorporated into future versions of the Vista Data Flow System archive.

This project will involve the use of large relational databases, many statistical methods and some simulation.

Further Information: WFCAM Science Archive: <http://surveys.roe.ac.uk/wsa/index.html>

VISTA Surveys:  
<http://www.eso.org/sci/observing/policies/PublicSurveys/sciencePublicSurveys.html#VISTA>

**Title: Structural Decomposition of Galaxies in the near-infrared.**  
**Area: Astronomy**  
**Supervisor: Dr. Nicholas Cross**

Galaxies are composed of many different structural components, including bulges, disks, bars and spiral arms. These components have very different dynamical states and star formation histories.

Studies which do not split the galaxies into these components find it difficult to disentangle the different populations and measure reliable masses and ages. Moreover the additional information from the different components put useful limits on models of galaxy formation.

The near infrared suffers less from the problems of dust absorption that plague optical surveys. The infrared light follows the underlying older stellar populations unlike optical light that is dominated by massive star forming regions.

This project will measure the structural properties of a small sample of infrared galaxies to show how the properties change with galaxy mass. The properties can also be compared to their equivalent optical counterparts to understand the changes in the stellar population between components.

The current largest infrared survey, the UKIRT Deep Infrared Sky Survey (UKIDSS) and the larger VISTA survey, which will commence this summer, will both be available for the student to use. The imaging and catalogue data are archived at the IfA as part of the VISTA Data Flow System.

There is also a large amount of spectroscopic and multi-wavelength data available for many of these galaxies through the GAMA project and related optical, UV and far infrared projects.

**Further information:**

UKIDSS: <http://www.ukidss.org/>

VISTA: <http://www.vista.ac.uk/>

GAMA: <http://www.eso.org/~jliske/gama/>

WFCAM Science Archive (UKIDSS data): <http://surveys.roe.ac.uk/wsa/>