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Cover illustrations

Front - The ‘Einstein Window’ in the Hall at Christ Church. (Reproduced by permission of the Governing Body of Christ Church, Oxford)

Rear - The blackboard which Einstein used in his Lecture on Relativity given at Oxford in 1931. (reproduced by permission of the Museum of the History of Science)

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Introduction

The Physics Department of the University of Oxford is one of the largest physics departments in the United Kingdom and in the world. It has a lively and active programme in both research and teaching. The research described in this booklet is supported by substantial funds from the Research Councils, Europe and industry and the whole programme was given a 5* rating, the highest possible rating in the last assessment exercise, for quality in the national research selectivity exercise. We have 70 members of academic staff (Professors, Readers and Lecturers) whose work is supported by about 100 technical and secretarial staff, and 200 postdoctoral staff and engineers, who work closely with over 200 students studying for the post-graduate DPhil degree.

The Department is organised into the following six sub-departments:

Astrophysics

Atmospheric, Oceanic & Planetary Physics

Atomic and Laser Physics

Condensed Matter Physics

Particle Physics

Theoretical Physics

Although much of the theoretical work is concentrated in Theoretical Physics, part is done in the other sub-departments. The detailed programme of the novel and successful research in all these areas is described in this book.

Further details can be obtained from the Heads of the sub-departments at the addresses listed on page 4, or from individual members of staff named in this book.

Prospective graduate students wishing to apply to Oxford who have already chosen a specific field of study should write to the appropriate sub-department as listed on page 6; those who are interested in the work of several sub-departments, or have general questions, should write to Mrs C. Leonard-McIntyre, Denys Wilkinson Building, Keble Road, Oxford, OX1 3RH (c.leonard-mcintyre1@physics.ox.ac.uk).

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ASTROPHYSICS

Professor Roger Davies and Professor Joseph Silk

Research in this sub-department spans almost the whole range of astronomy, from the largest scales in the Universe to observational work on stars and the interstellar medium. There are, therefore, ample opportunities for students wishing to pursue research leading to the DPhil degree. The Sub-Department of Astrophysics consists of over 50 research-active staff, of whom 10 are established university appointments (permanent), 18 are post-doctoral researchers and 20 are research students. There are two statutory Professorships, the Savilian Professorship (held by J. Silk since 1/1/99) the newly created Philip Wetton Chair in Astrophysics, to which R. L. Davies has recently been appointed. In addition, there are several astrophysicists in the Sub-Department of Theoretical Physics; those involved are flagged with an asterisk and further details of their work can be found in the Theoretical Physics Section of this booklet.

The Astrophysics Sub-Department is situated in the Denys Wilkinson Building which is close to the centre of Oxford and the extensive University Parks. The Laboratory has excellent library, teaching and workshop facilities. The Sub-Department has grown steadily in recent years. J. Silk, Head of Astrophysics, has established a theoretical research group studying cosmology, galaxy formation and dark matter. We are also fortunate in having excellent access to a powerful complement of computer systems for data analysis, modelling and simulations.

Oxford Astrophysics has been successful in attracting long-term Royal Society, PPARC Advanced and other Senior Research Fellows funded by a grant from the Leverhulme Trust. A PPARC rolling grant supports research into observational cosmology. We are taking a major role in the construction of the UK-Japan near-infrared, fibre-fed, multi-object spectrograph, FMOS, for the 8m Subaru telescope. Oxford is also a partner in consortia designing and building second generation instruments for the European Southern Observatory's VLT and the Gemini telescopes, notably KMOS, MUSE, WFMOS and ExAOC. We have also won a Marie Curie Excellence Grant from the European Commission for realising SWIFT, a novel integral field spectrograph. Oxford is the coordinating node for CMBNET, a European network for collaborative research into the cosmic microwave background, and for the Early Universe European network for particle cosmology. Oxford also is a node in two other European networks on Type 1a Supernovae (theory and observation), and SISCO: Spectroscopic and Imaging Surveys for Cosmology.

Members of the sub-department have been very successful in gaining observing time on most of the large aperture ground-based telescopes, including the Anglo-Australian Telescope (AAT), the William Herschel Telescope (WHT), the United Kingdom Infrared Telescope (UKIRT), and the new generation of 8m class telescopes (Gemini, Subaru, and VLT) for optical and infrared observations, as well as the James Clerk-Maxwell Telescope (JCMT) for sub-millimeter imaging. Many hours have been awarded to Oxford astronomers on the Very Large Array (VLA) at radio wavelengths and recently we have been using Very Long Baseline Interferometry (VLBI) techniques with the Multi-Element Radio-Linked Interferometer Network (MERLIN) and the Very Long Baseline Array (VLBA). Members of the sub-department are involved in observations from space over a very wide range of wavelengths, with ASCA, XMM and Chandra (for X-ray observations), the Hubble Space Telescope (HST) (for infrared, optical and ultraviolet astronomy), and in the preparations for the PLANCK mission to study the cosmic microwave background. The UK Gemini Support Group is located at Oxford. In theoretical astrophysics, there are strong programmes in the area of galaxy dynamics, cosmology, galaxy formation, dark matter and the cosmic microwave background radiation. The recent appointment of R.L.Davies will lead to an expansion in extragalactic astronomy and astronomical instrumentation.

1. Observational cosmology and galaxies

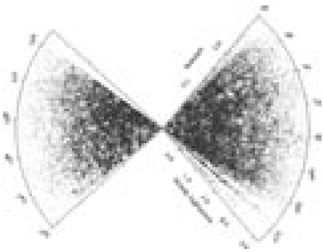
J Baker, K Blundell, G Cotter, G Dalton, R Davies, I Hook ,R. Johnson, L Miller, S Rawlings, N Thatte, S Yi.

1.1 Motivation

Theory provides predictions of the spectrum of fluctuations in the matter distribution of the Universe, but testing these predictions by making observations is by no means straightforward. The matter fluctuations may be traced by making surveys of galaxies, clusters of galaxies, quasars or radio sources. Determination of the three-dimensional structure of the Universe requires surveys covering a large fraction of the observable Universe, and these surveys must account for a variety of biases and projection effects. Problems encountered range from those that are conceptually simple but observationally challenging - such as the requirement of redshift information for a large number of objects - to those that are subtle such as the distortions due to gravitational lensing of distant objects by the intervening matter distribution. At Oxford we are, for example, studying the structure of the Universe using Type 1a Supernovae. The present paradigm for galaxy formation and evolution has galaxies assembling in their dark matter halos as these merge to form ever more massive objects over cosmic time. The Hubble Space Telescope (HST) has shown us that galaxy interactions and mergers were more common in the distant past and that these events are frequently associated with star formation episodes. How the luminous components of galaxies come to have their present appearance, why some have disks and others do not and when the major star forming episodes occurred are some of the central goals of our observational work on galaxy evolution. In addition to using normal and active galaxies as cosmological probes, there are a number of programmes at Oxford which aim to improve our understanding of how active galaxies work. Key questions include: why do only some active galaxies develop powerful radio-emission; what is the link between extranuclear star formation and nuclear activity; is there a link between the mass and structure of the host galaxy and the type of nuclear activity; why were there large changes in the space density of active galaxies with cosmic time? These programmes require observations at all wavebands, and often at the high angular resolution offered by Very Long Baseline Interferometry at radio wavelengths or the HST in the infrared, optical and ultraviolet wavebands.

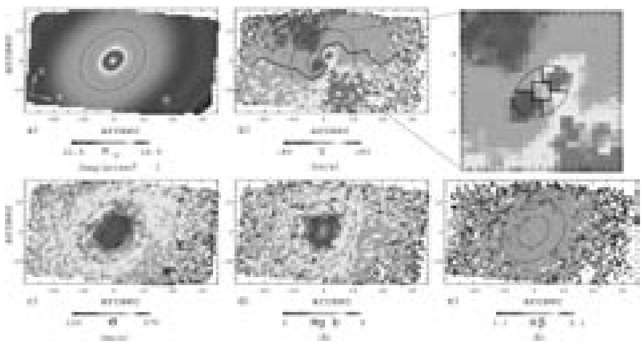
1.1.1 Galaxy surveys

Our group is working on a number of surveys of large-scale structure as traced by galaxies and clusters of galaxies, both nearby and distant. The aim of this research is to study the formation and evolution of galaxies and their large-scale distribution. One of these surveys uses the two-degree field (2dF) facility at the Anglo-Australian Telescope, which allows simultaneous measurement of the spectra of several hundred galaxies over that field. The Anglo-Australian 2dF Redshift Survey aims to measure redshifts for at least 250,000 galaxies; this will provide the first three-dimensional measurements of galaxy clustering on the large scales that may be studied at early cosmic epochs by measuring fluctuations in the microwave background. As we probe the galaxy distribution to fainter magnitude limits, the study of galaxy clustering is affected by the evolutionary histories of the galaxies themselves, as we see more distant objects at earlier times. The combined effects of cosmological redshift and galaxy evolution imply that multicolour surveys of faint galaxies are required to trace the evolution of galaxy clustering. We are in the process of constructing a deep wide-field optical and infra-red survey of faint galaxies. This will be used to identify candidate clusters of galaxies at a range of cosmological epochs, which will be followed up using the new generation of 8 m telescopes to study the evolution of galaxies and galaxy clustering.



A slice of the Universe showing nearly 200,000 galaxies from the 2dF Galaxy Redshift Survey. In addition to the three dimensional positions of galaxies, the survey contains a wealth of information on the nature of each galaxy, including luminosity and star-formation history. The survey represents a comprehensive snapshot of the local Universe to which future surveys can be compared to study the evolution of galaxies.

Local galaxies can be studied with greater precision and linear resolution than high redshift galaxies allowing us to make connections between their structure, dynamics and star-formation history. Our work seeks to characterise and model local galaxies as a function of luminosity, environment and Hubble type. In this work we apply the latest instrumental techniques that allow us to take a spectrum at every point in a galaxy simultaneously (using Integral Field Spectrographs, IFS) to produce a map of the velocity field and composition of the gas and stars. We are also able to estimate the age of the stars that dominate the integrated light. A few galaxies have core regions with stellar kinematics that are completely decoupled from those of the rest of the galaxy and this is taken as an indication of a past merger, but when did it occur? NGC4365, shown in the figure, is a good example. The velocity map shows that, this otherwise ordinary galaxy is rolling around its long axis but the central regions are rotating roughly perpendicular to this! The lower right panel shows that the strength of the Hβ Balmer absorption line is constant across the entire galaxy, both the decoupled core and main body. This shows that the stars in both components are the same age. It is very likely that the decoupled kinematics arose from a merger but character of the stars tells us this happened 12-14 Gyrs ago in the initial star forming event and that the galaxy has been quiescent since. The core is a remnant of the formation process, not the result of a late merger. Thus by measuring both the kinematics and the ages of the stellar population we are able to deduce the evolutionary history of galaxies. That work used the purpose built {SAURON} spectrograph on the William Herschel Telescope with which we



NGC 4365 - A good example of a galaxy having a core region with stellar kinematics that are completely decoupled from those of the rest of the galaxy.

are pursuing an extensive survey. We plan to use IFS on the 8m Gemini and VLT telescopes to extend this work to higher redshift galaxies and into the infrared allowing us to "age" and "weigh" distant galaxies to test the assembly paradigm directly. Through this work we have developed precise techniques for determining the mass-to-light ratio of galaxies, their ages and compositions all of which can be adapted to measure the evolution of galaxies directly by studying the galaxy population in groups and clusters at high redshift. We know that the galaxy population in dense regions of the universe is quite different from that in regions of average density but we do not know why. Through statistical studies of galaxies in different environments over a range of redshift we can eliminate candidate mechanisms. We use the luminosity in X-rays to signal the presence of a true physical association at high redshift and to determine the local density of the intergalactic medium. By using multiple object spectroscopy at both optical and infrared wavelengths we can assemble large galaxy samples for this work.

1.1.2 Quasar surveys

Quasars are the most luminous objects known. They are the most extreme form of active galaxy in which a galaxy's nuclear region can generate 1000 times more light than all the stars in that galaxy. Some of them are the most distant objects yet discovered, making them useful probes of changes in the Universe with time. Quasar surveys at optical, radio and X-ray wavelengths are being revolutionised in size: e.g. the collaborative 2dF quasar survey will eventually produce a sample of 24,000 optically-selected quasars. This large number is needed so that we can study how the clustering of quasars changes with cosmic epoch, which can be used to compare with theoretical predictions, as well as placing quantitative limits on the parameters that describe the geometry of the Universe and allowing greatly improved determination of the cosmological evolution of the population of quasars.

1.1.3 Radio source surveys

Like quasars and other active galaxies, luminous radio sources are also concentrated in the younger Universe. Oxford workers are pursuing programmes to study the most distant examples of these objects. These are seen at times when the Universe was only about one billion years old, and are thus important for studying the earliest observable phases of galaxy formation. We study these objects across the electromagnetic spectrum using the largest ground-based optical and radio telescopes, and space-based facilities such as the HST, Chandra and XMM satellites, as well as infra-red and sub-mm imaging. We aim to disentangle the effects of the radio activity, and the active nuclei which power them, from the underlying starlight. In particular, we have made the first redshift surveys of faint radio galaxies. These have yielded high-redshift radio galaxies whose host-galaxy light should be less affected by the active nucleus, and whose properties give direct information on the formation and early evolution of elliptical galaxies. We are also determining how the entropy injected into the intergalactic medium by jets influences galaxy formation and evolution. We are also using the new generation of high-frequency surveys to identify sources whose radio jets have very recently been triggered.

1.1.4 Physical models of quasar and radio source evolution

It has been recognised for 30 years that the space density of quasars was much higher in the past than at the present day. When the Universe was about one-third of its present age there were about 100 times more quasars of a given luminosity than there are today, after allowing for the expansion of the Universe since that time.

The quasar and radio source surveys described above give us quantitative information on the amount of that evolution but tell us little about how and why it occurs. To tackle this problem we need both a physical model for the evolution of quasars, radio sources and active galaxies, and also we need new observational information. Key to our understanding are the links between host galaxy type, mass and environment, nuclear activity and starburst activity. New ground-based infrared and submillimetre observations are shedding new light on this problem, together with Hubble Space Telescope infrared imaging of quasar host galaxies.

1.1.5 Radio galaxy and quasar companions at high redshift and distant clusters

Active galaxies are frequently found with normal galaxy companions or in clusters of galaxies, and Oxford workers are leading projects aimed at identifying and studying companion galaxies over a large range in redshift. At moderate redshifts, clusters can be imaged directly in the optical and we have found many quasars and radio sources in clusters of galaxies. This may provide an important clue to the origin of the rapid rise in number density of quasar activity with redshift, for example it might pinpoint the epoch at which rich clusters first formed. At higher redshifts clusters can be detected by multi-colour near-infrared imaging, and star-forming companion galaxies may be detected using narrow-band imaging techniques to isolate strong emission lines. We are also involved in the study of high-redshift clusters selected by their imprint on the Cosmic Microwave Background.

1.1.6 The nuclear environment of nearby active galaxies.

Active galactic nuclei are thought to be powered by massive black holes. However, star formation can sometimes play a major role in the energetics of the nuclear region. By conducting high resolution observations using adaptive optics at near infrared wavelengths, Oxford researchers are studying the close-in nuclear environment of active galaxies. Besides measuring the fraction of nuclear luminosity attributable to star formation, these observations also address the issue of fuelling of the active nucleus. The mechanism for transporting gas from ~100 pc scales to the immediate vicinity of the black hole is not well understood, although bars and Linblad resonances do play a vital role. Spectra of the close nuclear environment also provide kinematic information about gas in the narrow line region, and allow us to probe the physical conditions and excitation mechanisms of the circumnuclear environment.

1.1.7 Demographics of supermassive black holes in ngalaxy nuclei.

Super-massive black holes (with masses from a few million to a few billion solar masses) are thought to lurk in the nuclei of all present day galaxies. A recently established empirical relationship shows a tight correlation between the mass of the super-massive nuclear dark mass and the total mass of the galaxy bulge. Yet it is unclear as to what physical processes collude to link two quantities whose size scales differ by a factor of more than a million. Oxford researchers are carrying out a co-ordinated program to build up a larger sample of black hole mass measurements, especially at the low and high mass ends, to explore the dependence of black hole mass on galaxy morphology, level of activity, radio properties etc. Integral field and long slit data at near infrared wavelengths, where dust extinction is less significant, are being used to probe the nuclei of spiral galaxies, thus complementing present work that has concentrated on early-type galaxies. The program is being extended to use adaptive optics techniques to substantially improve the spatial resolution of the observations. By probing the stellar dynamics of galaxy nuclei at spatial scales corresponding to the sphere of influence of the central black hole, we hope to unravel the physics that underlies the observed correlation.

1.1.8 Weak and strong gravitational lensing

The observation that high luminosity, high redshift active galaxies seem to have more foreground galaxies projected close to their line of sight than expected by chance has been a long-standing puzzle. One possibility is that gravitational lensing of background quasars and radio galaxies by foreground groups and clusters of galaxies may magnify their flux. If this is true, we would expect to be able to identify the presence of such mass concentrations using X-ray observations, observations of decrements in the microwave background or through their distorting effect on the images of other background galaxies in the field. Oxford workers are pursuing all these possibilities. If foreground galaxies are close enough to the line of sight then strong gravitational lensing effects come into play. There are several examples of strong lensing in the Oxford quasar and radio galaxy surveys, and these are being used to measure the mass-to-light ratio in distant galaxies and clusters.

1.1.9 Measuring cosmological parameters using type Ia Supernovae

In the last five years the use of Type Ia supernovae as standard candles has provided evidence that the expansion of the Universe is accelerating. This initially unexpected result hinges on the observation that distant supernovae appear fainter than would be expected in a non-accelerating universe. Work is now underway to understand and extend this result by studying supernovae in detail at high redshift. One of the most important issues to understand is the extent to which dimming by dust may be affecting the results. Researchers in Oxford are working in collaboration with colleagues around the world on major surveys to find and study distant supernovae, using the world's leading observational facilities.

1.1.10 Galaxy evolution using GALEX UV space telescope

NASA's space UV telescope satellite, GALEX, is performing an unprecedented all-sky UV survey. Since its launch in April 2003, it has been collecting the UV spectra and images of hundreds of thousands of galaxies and stars. Its main science topics include the star formation history of the universe and of individual galaxies. Our team in Oxford led by Yi is working on the star formation history of early-type galaxies which have been believed to be quiescent (no recent star formation). Surprisingly, we found at least 15% of bright early-type galaxies show unambiguous signs of recent starbursts; this very interesting result is stimulating us to make various further tests and investigations.

1.2 Theoretical astrophysics and cosmology

J Binney, G Bryan, J Magorrian*, P Ferreira, J Silk, S Yi*

This group's research concerns the dynamics under gravity of all astrophysical systems that are not extremely relativistic. It includes the formation of large scale structure in the Universe, the formation of galaxies, galaxy evolution, the dynamics of the Milky Way and other galaxies, gravitational lensing and the long term evolution of the Solar System. Much of this research is driven by observations from the new generation of telescopes and instruments, including the HST and preparation for future missions, such as ALMA, PLANCK, NGST, and the new generation of cosmic microwave background experiments. The modelling involves both analytical and numerical work, with modern theories of non-linear dynamics playing a unifying role.

1.2.1 Cosmic microwave background

The origin of large-scale structure may be probed by studying trace fluctuations in the cosmic microwave background. These are imprinted by primordial irregularities in density that grew by gravitational instability in the early Universe. The increasingly refined measurements of anisotropies that have been detected over a range of angular scales are beginning to constrain and even challenge theoretical models. Planned radio and submillimetre wavelength experiments using telescopes on balloons (the recent BOOMERANG experiments), satellites (MAP in 2001 and Planck in 2007) and ground-based interferometer arrays will approach a level of sensitivity that will definitively measure many, if not all, cosmological parameters with unprecedented precision. One of the major uncertainties is that of foregrounds, both galactic and extragalactic, which need to be evaluated in order to enhance the precision of such measurements. Simulations of sky maps will be one of the activities that will be undertaken at Oxford. In a complementary attack on large-scale structure, the deep galaxy redshift surveys now underway and which will obtain of order a million redshifts have the sensitivity to probe large-scale power in density fluctuations in the nearby Universe. The physical scales that are studied in this way overlap with the power spectrum inferred at high redshift from mapping of the cosmic microwave background, and combination of the two approaches will provide new insights into models for large-scale structure. On small angular scales, early formation of galaxy clusters, radio galaxies and quasars inevitably provide energy input into the intergalactic medium and generate fine-scale temperature anisotropies. Understanding the detailed nature of such signatures will help define a goal for new generations of experiments and satellite missions.

1.2.2 Galaxy formation

Understanding how galaxies form and unravelling the nature of the origin of the large-scale structure of the Universe are key unresolved issues in cosmology. A focus of our research includes the study of galaxy formation and evolution. The challenge of galaxy formation theory is to account for the fossilised properties of galaxies, such as morphologies, scaling relations, and chemical abundances, as well as the evolution of these properties with redshift. The star formation histories of disk and elliptical galaxies and their high redshift counterparts provide vital clues to galactic evolution. Semi-analytical techniques can be applied to yield global star formation rates in disk galaxies and evolve nearby galaxies backwards in time. Galaxy mergers induce ultraluminous starbursts, and study of such phenomena, including the roles of infall, galactic winds and active nuclei, provides insight into spheroid formation. An improved understanding of protogalaxy evolution will have profound implications for understanding chemical evolution and for interpreting far infrared and submillimetre observations of star-forming galaxies in the distant Universe.

1.2.3 Dark matter

The frontier of particle physics is beyond the TeV energy range of current generations of accelerators but in the realm of the energy scales of supersymmetry or grand unification, or even quantum gravity. The interface of cosmology and particle physics plays a critical role in motivating such research. These seemingly diverse realms coincide in the Big Bang cosmology, which provides a unique particle accelerator that operates up to energies of 10^{19} GeV. The study of the early Universe thus provides a unique laboratory for searching for relics from very early epochs for testing ideas from such theories as grand unification and supergravity. Perhaps the most important development has been that of the inflationary cosmology, which may solve a number of outstanding problems that have puzzled cosmologists for over half a century. These include the isotropy of the Universe, its size, its homogeneity on large scales and its lack of homogeneity on small scales, and the paucity of bizarre relics such as monopoles. Predictions of inflationary cosmology, such as the origin and spectrum of density fluctuations and the distribution and composition of dark matter, are important to the understanding of galaxy formation and sensitively depend on the details of the correct particle theory. The particle relics from the beginning of the Universe may surround us today in the form of dark matter in galaxy halos. One current study explores the hypothesis that the dark matter in our galactic halo and in the halos of nearby galaxies consists of massive stable relic particles which occasionally annihilate to produce a substantial flux of sub-GeV cosmic ray antiprotons, high energy gamma-rays and neutrinos with unique spectral signatures.

1.2.4 External galaxies

In recent years, galactic astronomers have become more aware of the importance of cusps in the centres of galaxies. First, computer simulations of halo formation in hierarchical clustering cosmogonies have revealed the existence of a universal, cusped profile for galactic haloes. Secondly, there is an extensive data-set of images of galactic nuclei taken with the HST. The brilliance of the central nuclei is a consequence of a power-law rise in the light distribution right down to the very limits of the resolution. Researchers in Oxford have been actively involved in the understanding and the modelling of dynamics in the cusp. There are several suggestions as to the origin of galactic cusps; perhaps some are caused by the presence of black holes, while some may be the result of the engulfment of gas-rich, small disk galaxies. Another intriguing possibility is that the cusps are a natural end-point of the process of merging and accretion that built the galaxies. The shapes of external galaxies depend on their orbital populations. These populations change through capture into and escape from resonance. Resonances are important in both galactic and Solar System dynamics, as small disturbances can have a dramatic effect on orbital shape at resonance. For example, tidal resonant forcing of highly inclined orbits around a central black hole can cause a substantial increase in the likelihood of collision. This may be an important means of fuelling the black holes that are believed to reside in galactic nuclei. Workers in Oxford have developed a new pictorial form of non-linear perturbation theory that enables us to study motion close to a resonance and to make predictions of dynamical behaviour that can be compared with numerical simulations. Why are some galaxies barred, and some are not? Why are some galaxies lop-sided, and others not? The question of the origin of non-axisymmetric structures has led us to undertake detailed stability analyses of models of stellar systems. These include normal mode studies of the linear stability problem, as well as brute force N-body calculations.

1.2.5 The Milky Way

The Oxford workers are engaged in a long term project towards a comprehensive understanding of the Milky Way. Over the last decade, Binney and co-workers have been developing a new method (the Oxford Torus Project) to analyse the stellar kinematics of nearby stars. When stellar motion is viewed in a six-dimensional phase space of positions and momenta, it is particularly simple. The stars move on three-dimensional tori. This feature is preserved under slow adiabatic perturbations. By adjusting the distributions of stars on tori, models are obtained for the interpretation of the kinematics of stars in the Milky Way. Another area undergoing rapid development is the study of the Bulge of the Milky Way. The DIRBE instrument that flew on the COBE satellite provided the most detailed picture to date of the Galactic Bulge. This is evidently asymmetric; for example, the infrared light distribution is brighter towards positive longitudes than negative longitudes. This was striking confirmation of a viewpoint earlier advanced in Oxford and elsewhere that the Milky Way galaxy is barred, with the near-side of the bar lying towards positive longitudes. A major effort (the Oxford Bar Project) aims at developing a series of stellar dynamical models of the inner Galaxy and using them to interpret the radial velocity and proper motion data towards the Galactic Centre. The microlensing surveys are a very new and important source of information on the Milky Way. So far the dynamical implications for our galaxy are not well understood, and Binney has been in the forefront of the struggle to understand these data using models developed both for the dark halo and the Bulge.

1.2.6 Galaxy Spectral Evolution

At Oxford, we also have a group (with one lecturer and two PDRAs) that focuses on constructing the spectral evolution models of galaxies. The main technique is the evolutionary population synthesis (EPS) which numerically computes the integrated spectrum of a galaxy as a function of time, following star formation history, initial mass function, and individual stellar evolution. The predicted synthetic spectra are currently the most powerful tools to study galaxy evolution. Outstanding tasks include age estimation of old galaxies near and far. The spectra trace visible matter, whereas the mass distribution may be dominated by dark matter. Therefore, comparing the knowledge obtained from galaxy spectral analyses to that from dynamical modelling and kinematic observational data may allow us to find the link between luminous matter and dark matter.

2 Stellar Astrophysics

A Lynas-Gray, P Podsiadlowski, S Yi.

2.1 The evolution of single and binary stars

We have several projects studying the various phases in the evolution of stars, starting with the basic formation process to their final phase, the planetary-nebula or supernova stage. We are particularly interested in applying stellar evolution theory to stars in binaries to see how binary interactions can affect the structure and evolution of stars, for example, to explain the origin of stars with chemical anomalies (e.g. barium stars) or to explain the non-spherical, often bipolar morphologies of many planetary nebulae. In these studies, we use a variety of analytical and numerical tools (specially modified stellar structure codes, hydrodynamical codes in one to three dimensions) and maintain active collaborations with various theoretical and observational groups around the world. At present, the two major applications of this work are the study of pre-supernova evolution in interacting binaries and X-ray binaries.

2.1.1 Supernovae

There are two fundamentally different types of supernovae: thermonuclear explosions which occur when a white dwarf is pushed above its maximum mass of 1.4 solar masses (the Chandrasekhar limit) and which leads to the complete disruption of the star (referred to as a ‘Type Ia supernova’), and core-collapse supernovae which take place when the core of a massive star has exhausted all of its nuclear fuel. In the latter case, the core of the star collapses to leave a compact remnant, a neutron star or in some cases a black hole. A small fraction of the energy released in the collapse is deposited in the envelope, leading to an explosion and the bright, spectacular display we refer to as a supernova. The appearance of the supernova, however, depends sensitively on the pre-supernova structure of the envelope and hence the star's evolutionary history in a binary. The various binary interactions (mass loss, mass accretion and merging) can fundamentally change the structure of a massive star and may thereby account for many of the observational supernova sub-classes.

We are particularly interested in applying this theory to two of the most interesting nearby supernovae of our generation, SN 1987A and SN 1993J. SN 1987A was the first naked-eye supernova since Kepler's supernova in 1604 and is a highly anomalous supernova. Contrary to what had been predicted, the progenitor was a blue supergiant instead of a red supergiant, and is surrounded by a spectacular, but very complex, nebula consisting of three bright rings (seen most clearly with recent HST images) and has various chemical anomalies in its envelope. At the moment, these anomalies can be best explained if the progenitor originally was in a binary and has merged with its companion in the not-too-distant past. We are actively modelling all the detailed physical processes involved in the merging of two massive stars, in particular the dynamical evolution of the system in the merger phase, the associated anomalous nucleosynthesis and the dynamical ejection of part of the envelope, presumably producing the triple-ring nebula around the supernova.

The progenitor of SN 1993J on the other hand seems to have been a star mainly consisting of helium and heavier elements with a very small hydrogen-rich envelope. This again suggests that it was a member of a binary and that it lost most of its hydrogen-rich envelope by mass transfer. In both cases, future observations and theoretical calculations will be required to confirm or refute the suggested binary connections.

Type Ia supernovae have recently been used as cosmological distance candles (See Section 1.1.9) to measure the curvature of the Universe. At face value, the results suggest an accelerating Universe, a dramatic break from the previous picture. However, these results do not take into account possible evolutionary changes in the population of Type Ia supernova progenitors. Considering that there is no agreement on what the progenitor systems of these supernovae actually are, this seriously weakens the cosmological argument. We are presently studying various types of binary systems proposed as progenitors for Type Ia supernovae and model the evolution of the population of these progenitors since the early Universe, using binary population synthesis methods.

Hypernovae are a rare, new supernova type, first identified in 1998, which are much more energetic than a normal supernova and are probably caused by the collapse of a rapidly rotating helium star to a stellar-mass black hole. Some hypernovae are observationally known to be related to gamma-ray bursts, the most violent and most energetic events known in the Universe. Again our main interest is in understanding what type of stellar system can produce the progenitors of these spectacular events.

2.1.2 The formation and evolution of X-ray binaries and millisecond pulsars

Recent observations of the space velocities of pulsars (rapidly rotating neutron stars) have shown that when neutron stars are born in a supernova they receive very large kicks (presumably due to an asymmetry in the supernova explosion). This has important effects on the orbital parameters and the Galactic distribution of neutron stars in binaries. We are particularly interested in so-called low-mass X-ray binaries (LMXB), where a low-mass star with the mass of the Sun or less transfers matter to a neutron star, which as a result becomes a luminous X-ray source. While supernova kicks are important for understanding the formation of LMXBs in the Galactic disc, in dense stellar environments like globular clusters, other processes may be more important. For example, in globular clusters, LMXBs may form as a result of the tidal capture of a neutron star by a normal star. However, whether this is a viable process depends on the response of the normal star when the tidal energy is deposited inside the star (the tidal energy can be a large fraction of the binding energy of the star). During the LMXB phase, it is generally believed that the neutron star is spun up by accretion of matter, leaving a millisecond pulsar once the X-ray phase has ended. However, statistical comparisons between millisecond pulsars and LMXBs suggest that there are either too many millisecond pulsars relative to the number of LMXBs or that the duration of the LMXB phase has been overestimated by a large factor. This latter, more likely, possibility may be understood by irradiation effects which can dramatically change the structure of the irradiated normal star. In particular, the secondary may become inflated which leads to accelerated evolution and a shorter duration of the LMXB phase. The details of this process depend, however, on the circulation inside the secondary caused by the one-sidedness of the irradiation in a binary. This is an important problem which we are actively studying at the moment, developing both the theoretical framework and the numerical tools to tackle this problem.

One of the most important recent discoveries in this field, which indeed may challenge the above paradigm for LMXBs, is the realization that many stars in so-called “low-mass” X-ray binaries originate from much more massive progenitors (e.g., Cyg X-2, Cyg X-3). Based on our recent calculations, it now seems that a large fraction, if not the majority, of low-mass X-ray binaries may actually belong to a much more massive, previously largely ignored class of intermediate-mass X-ray binaries, and that standard textbooks on the subject need to be rewritten. Apart from modelling individual systems, we use binary populations synthesis techniques to model the population of X-ray binaries (with US collaborators) and keep active collaborations with observational groups to test our predictions and improve our modelling efforts.

The formation of planets around pulsars (indeed, the first planets outside the solar system were discovered around pulsars) is a related problem of much current interest. Many massive X-ray binaries are predicted to merge in the near future. As a result of a complete merger, the neutron star sinks to the centre of the massive star forming a new hybrid object, generally referred to as a Thorne-Zytkow object (TZO). While no such TZO has yet been discovered, recent theoretical calculations predict that these objects should show anomalous surface abundances of many chemical elements which should be easily detectable spectroscopically. We are planning to use these predicted anomalies to search for these objects observationally.

2.1.3 Isochrone Project

One of the world’s most popular stellar isochrones (The Yale-Yonsei Isochrones) is in fact generated at Oxford at the moment as Yi moved to Oxford in 2001. Isochrones are defined as the locus of coeval (equal age) points on the evolutionary tracks of stars of different masses in the Temperature-Luminosity plane. Once accurate isochrones are constructed, one can use them to match the observed data of various populations to derive their ages. Most notably, isochrones are used to derive the ages of globular clusters in the Milky Way. Because globular clusters are often considered as the oldest populations in the universe, this allows us to set the lower limit on the age of the Universe. Not to mention the beauty of the stellar evolution theory behind the isochrones, there are numerous applications of isochrones, including isochrone synthesis for galaxy evolution modelling.

2.2 Stellar atmospheres

A knowledge of stellar abundances is crucial to our understanding of stellar and galactic evolution. While most stars have solar abundances or are metal-deficient with respect to the Sun, more pronounced abundance anomalies are also found. A few stars, for instance, have photospheres composed of 99% helium and 1% carbon (by numbers) with all other elements (including hydrogen) present only in trace amounts. Detailed abundance studies of stars in external galaxies (beyond the Magellanic Clouds) are becoming feasible using the HST and 10 metre class ground-based facilities. Improved techniques for the analysis of stellar spectra are under development; these take advantage of better computer hardware, numerical methods and (most important of all) recent advances in atomic and molecular physics. Synthesis of whole spectral regions with inclusion of all likely spectral features is now a viable method of approach.

Subdwarf-B (sdB) star research is of interest to investigations of stellar mass-loss, as these stars appear to represent extreme cases of near complete envelope loss during the later stages of stellar evolution. If most stars evolve through the sdB star stage, following evolution up the giant branch, understanding the envelope loss which results in sdB star formation is crucial to understanding the late stages of stellar evolution; it would also be the key to understanding chemical evolution of a galaxy or star cluster over several stellar generations. A recently published better understanding of sdB star evolution should help determine the contribution of sdB stars to the observed ultraviolet upturn in giant elliptical galaxies, with the view to its calibration as an age indicator. Following the exciting discovery of low-amplitude pulsation in seventeen sdB stars, the techniques of asteroseismology are being used to constrain stellar evolution models through a determination of envelope structure. The intention is to establish sdB star envelope structure by determining the dispersion relation of acoustic or gravity waves in surface layers, where wave scattering can be accurately computed.

3 Interstellar medium

P Roche

Tiny particles of cosmic dust permeate interstellar space and profoundly alter our view of many astronomical objects through the effects of interstellar extinction. However, the dust is not just a nuisance; the particles bear within them a record of the prevailing conditions where the dust was formed, ranging from the circumstellar shells of red giant stars to the cold molecular clouds where many complex molecules are synthesised. These species make important but poorly-understood contributions to interstellar chemistry and the energy balance of the interstellar medium. We are currently using the properties of the molecules and dust in planetary nebulae as probes of the processes and mechanisms which occur in intermediate mass stars at the end of their lives.

With the advent of sensitive infrared instruments, it has become possible to probe the chemical and physical structure of cosmic dust, and to investigate the sources lying within dust clouds, tracing the spatial extent and spectral properties of these dusty regions. These observations are particularly important in regions which are totally obscured at visible wavelengths such as the centre of our Galaxy, regions of star-formation in molecular clouds and the nuclei of dusty galaxies. Spectroscopy, imaging and polarimetry are employed to characterize these dusty environments and to investigate the objects lying in their cores. High resolution images obtained with the infrared cameras in Hawaii and La Palma are used to probe the nearest star forming regions on the scale of our own solar system. Models and Monte Carlo simulations of the effects of scattering by dust particles are developed to interpret the observations and provide information on the structures and geometry of the envelopes and disks around newly-formed stars.

4 Astronomical instrumentation

4.1 Infrared and visible wavelength instrumentation

G Dalton, R Davies, I Lewis, P Roche, M Tecza, N Thatte.

The astronomical instrumentation group at Oxford has expanded rapidly in the last year, with a strong influx of new personnel and new projects. We are now involved in designing, fabricating and deploying second generation instruments at three different 8-meter class telescopes - the European Southern Observatory's Very Large Telescope (VLT), the Gemini telescopes and the Japanese Subaru telescope. In addition, Oxford hosts the UK's Gemini Support Group which seeks to assist UK observers with preparation and exploitation of their Gemini programmes, putting us in an ideal position to exploit these facilities. We are also involved in a joint OPTICON-PPARC effort to define and develop science programs for the next generation of 30 and 100 meter telescopes (ELTs). The Oxford instrumentation group have recently won a Marie Curie Excellence Grant from the European Commission for the design and realisation of SWIFT, a novel integral field spectrograph. SWIFT will provide integral field capability covering the wavelength range 0.7 to 1.0 μm. SWIFT's novelty stems from the combination of a very high throughput image slicer based integral field unit, a CCD detector with very high sensitivity at red wavelengths, and the enhanced sensitivity and resolution afforded by an adaptive optics system. It is a fast track project, to be realised over a four year timescale. A dedicated team of 5 researchers has already begun working on the project. SWIFT will explore the kinematics and dynamics of galaxies at moderate and high redshift, using emission lines shifted into its bandpass. Additional financial support is also available from the University.

We are the principal UK partners with Japan in the construction of a wide-field, multi-object, infrared spectrograph project (FMOS). This will be fed by a robotic fibre-optic positioning system at the prime focus of Japan's 8.3m Subaru telescope. FMOS will see first-light in early 2005, and provides an excellent opportunity for a D.Phil student to become involved in the laboratory testing and science verification phase of the instrument which will address a wide range of science programmes from brown-dwarf stars to the evolution of galaxies at high redshifts.

Together with consortium partners in Germany (MPE, Garching and USM, Munich) and the UK (Univ. of Durham, UKATC) we have won a competitive bid to design and construct KMOS, the cryogenic, multi-object, near-infrared spectrometer for the ESO VLT. KMOS will be one of the VLT's second generation instruments, and will represent UK's major contribution to VLT instrumentation. KMOS will be equipped with deployable mini integral field units, thus providing spatially resolved information of over two dozen targets within a 7^{o} diameter field. Oxford will be responsible for the spectrograph module of KMOS, and for part of the data analysis and reduction software. KMOS is expected to be operational in 2009. We are also a major partner in MUSE, the Multi-Unit Spectroscopic Explorer, another second generation VLT instrument, led by R. Bacon (PI) in Lyon. MUSE will provide integral field coverage of 1′ x 1′ field of view with 0.″2 spatial sampling (almost 100,000 spatial elements!), whilst simultaneously covering the entire visible wavelength range in the spectral dimension (0.465 - 0.93 μm). The primary science driver for MUSE is to study emission line objects at high redshifts. These objects, with faint continua, are not easily detected in imaging surveys. MUSE also has a narrow field mode capable of observations close to the diffraction limit of the VLT, aided by its own adaptive optics system. Oxford is responsible for designing and developing the mechanical structure of MUSE. The project's instrument scientist is also at Oxford. Recently, our instrumentation group has been a partner in two successful bids for design and feasibility studies for Gemini second generation instruments. The first, termed ExAOC, is an instrument designed to perform direct imaging and spectroscopy of exo-solar planets using extreme adaptive optics, providing a contrast ratio exceeding 107 relative to the parent star. We will contribute an integral field unit to this instrument, which will allow simultaneous spectroscopy of all points within a couple of arc seconds of the parent star, at high spatial and moderate spectral resolution. The Phase A design study is on-going at the moment. We are also involved in a large consortium that will carry out a feasibility study for WFMOS, the most challenging of the Gemini second generation instruments. WFMOS will provide simultaneous spectra of ~5000 galaxies spread over a 1.5 degree field of view, in order to answer fundamental questions about the complexity of the Universe and to determine the equation of state of dark energy. It is a very ambitious project, as it will require major modifications to the Gemini telescope, and to the way in which the Observatory is run. At present, a feasibility study is being carried out.

Through a developing link with the CLRC's Rutherford Appleton Laboratory (also involved in the FMOS project) we are also contributing to the design and construction of a new 4m-class survey telescope (VISTA) which will be sited close to the VLT in Chile in 2006. VISTA hosts a uniqe wide field Infra Red camera which will be used to construct a deep survey of the entireSouthern sky to provide targets for the VLT, Gemini and the Next-Generation Space Telescope.

4.2 The UK Gemini Support Group

D. Baines, R. Bandyopadhyay, R. Johnson, I. Hook, D. Rigopoulou, P. Roche, I. Soechting

The UK is a 25% partner in the international Gemini Observatory which operates two 8-m telescopes on the best observing sites in the world, Mauna Kea in Hawaii and Cerro Pachon in Chile. The UK Gemini Supportgroup is based in Oxford and provides user support for all UK users of Gemini as well as some specialist support for the international Gemini community. The group also coordinates the UK scientific perspectives on the telescopes, instruments and operations and represents these to our international partners.

The first-light image of M74 from Gemini's GMOS instrument provides a taste of the ease with which superb quality scientific data can be obtained as Gemini moves into the phase of full operations.

ATMOSPHERIC, OCEANIC AND PLANETARY PHYSICS

Dr D G Andrews

The sub-department's research focuses on the study of physical processes in the atmospheres and oceans of the Earth and other planets, using experimental and theoretical techniques. We have about 70 members, including 10 permanent academic or research staff, about 20 post-doctoral researchers and senior visitors, and about 30 graduate students.

On the experimental side we develop space instruments for infrared remote sensing of the structure and composition of planetary atmospheres, especially the Earth's stratosphere and mesosphere. More than ten of these instruments have been launched, either into Earth orbit or to other planets; several new space experiments are under development, including Earth-orbiting instruments to investigate global change, and missions to Mercury, Venus and Mars. Extensive overseas and domestic collaborations are involved, with industrial and scientific centres in Europe and the USA.

We are an important centre for theoretical atmospheric and oceanic modelling. Our climate dynamics group studies the large-scale behaviour of the atmosphere-ocean system and its response to external drivers such as the increases in greenhouse gas levels responsible for anthropogenic climate change. Other modelling of the Earth's atmosphere focuses on large-scale dynamical and chemical-transport processes relevant to climate, and on the interpretation of our satellite data. We also use dynamical models of other planets, including Mars and Jupiter, to interpret existing data and help plan new observational missions.

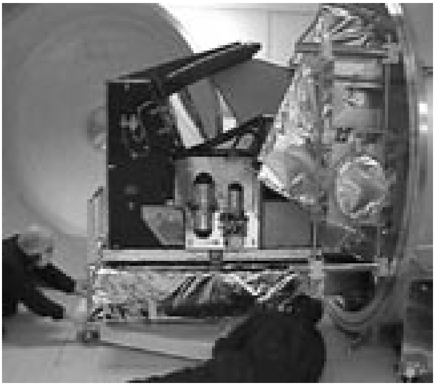
We also investigate fundamental geophysical fluid dynamics by means of laboratory experiments on rotating, stratified fluids.

1 Space and ground-based experiments for observing the Earth and its atmosphere

J J Barnett, A Dudhia, R G Grainger, G D Peskett, F W Taylor.

High resolution dynamics limb sounder (HIRDLS)

The sub-department is collaborating with other groups in the UK and USA on the HIRDLS remote sounding satellite instrument, launched in mid 2004 on the EOS Aura satellite as part of NASA's Earth Observing System. HIRDLS measures the concentration of trace species, temperature and pressure variations in the Earth's atmosphere between about 8 and 100 km altitude. Its primary aim is to measure at a much finer spatial scale than previous instruments, to about 1 km vertical resolution and 500 km horizontally. Oxford is taking the scientific and technical lead in the UK, with the Rutherford Appleton Laboratory, Reading University, Astrium and GEC-Marconi playing major roles. The University of Colorado is taking the lead in the USA, with the National Center for Atmospheric Research, the University of Washington and several aerospace companies undertaking major activities. Part of the hardware was built at Oxford and we performed extensive pre-launch calibration of the instrument, using our purpose-built laboratory and test equipment. In addition we are undertaking a number of software tasks concerned with flight operations and data processing.



The HIRDLS satellite instrument being loaded into a vacuum chamber in the satellite instrument test laboratory.

Tropospheric emission spectrometer (TES) and Michelson interferometer for passive atmospheric sounding (MIPAS)

In a collaboration with colleagues in California, a high-resolution, cooled Michelson interferometer (TES) is being developed to study a range of tropospheric minor constituents and hence to understand the chemistry of the polluted lower atmosphere. Work at Oxford is concentrating on the conceptual design of data analysis methods. TES was launched in 2004 on the same spacecraft as HIRDLS.

MIPAS is one of the core experiments on ESA's Envisat satellite, launched in March 2002. It measures infrared atmospheric limb emission spectra over an altitude range 6-68 km; the primary goal is to obtain profiles of atmospheric temperature and concentrations of CH_4, H_2O, HNO_3, N_2O, NO_2 and O_3 in near-real-time. A key feature of MIPAS is that it provides the first global set of spectrally-resolved data; in principle this means that concentrations of many other species can also be retrieved, as well as isotopic ratios, vibrational temperatures, distribution of aerosol particles, tropospheric cirrus, and stratospheric ice clouds (including polar stratospheric clouds). Oxford has worked closely with other European groups in developing the retrieval algorithm, with particular contributions to the radiative transfer modelling, microwindow selection and error analysis. We continue to provide support for validation and future improvements in ESA's operational processing and we have also developed our own retrieval algorithms to explore the additional information contained in the dataset. One of our interests is to use MIPAS data to determine the properties of cloud in the upper troposphere.

Improved stratospheric and mesospheric sounder (ISAMS)

This sophisticated infrared radiometer measured temperature and trace chemical profiles in the stratosphere and mesosphere, using the 'pressure modulation radiometry' technique that was developed here and used on several previous space instruments. We designed, built and tested ISAMS in collaboration with the Rutherford Appleton Laboratory and British Aerospace; it was launched on NASA's Upper Atmosphere Research Satellite in 1991.

Current applications of the data include the use of aerosol extinction data by the European Commission projects MAPSCORE and PARTS; these are concerned with the formation and physical, optical, and chemical characteristics of stratospheric aerosols and polar stratospheric clouds.

Along-track scanning radiometer (ATSR)

We helped design the ATSR in conjunction with the Rutherford Appleton Laboratory, the Met Office and the Mullard Space Science Laboratory of University College, London. It was tested and calibrated at Oxford, and launched on the ESA Remote-sensing Satellite ERS-1 in July 1991. A second instrument, ATSR-2, also calibrated at Oxford, was launched in 1995. Aerosol and cloud properties are being retrieved from 7½ years of ATSR-2 data as part of the NERC project GRAPE. The ATSR mission was extended in 2002 with the launch of the Advanced ATSR on Envisat; current studies are exploiting the four additional channels on AATSR to improve the accuracy of retrieved atmospheric properties

2 Space experiments for observing the planets

S B Calcutt, P G J Irwin, S R Lewis, P L Read, F W Taylor

Exploring Mercury from orbit

Oxford scientists are part of the European Space Agency team developing the ‘BepiColombo’ mission to the planet Mercury. Our role involves infrared radiometry to characterize the physical properties of the surface and determine the nature of the icy deposits at the poles. We also aim to determine the heat flow from the interior of the planet, which is expected to be anomalous since Mercury has a substantial magnetic field and a very large and partially liquid core.

European mission to study the atmosphere of Venus

With colleagues in France and Germany we proposed the Venus Express mission, which is now approved and under construction by the European Space Agency for launch in 2005. It will study Venus from orbit for three years, beginning in March 2006. The main focus of the mission is to seek to understand the climate on Venus, which is not at all what would be expected by extrapolating from the Earth. In particular, we will study the nature of the global atmospheric circulation, the atmospheric chemical composition and its variations, surface-atmosphere physical and chemical interactions including volcanism, the physics and chemistry of the cloud layer, the thermal balance and role of trace gases in the greenhouse effect, and the origin and evolution of the atmosphere. Progress on these issues is of crucial importance in a comparative-planetology context, notably for understanding long-term climatic evolution processes on Earth-like planets

Surveying the climate of Mars

The department plans to make a third attempt to deploy an infrared remote sounding instrument in orbit around Mars. Mars Climate Sounder (MCS) is currently scheduled for launch in 2005 on the Mars Reconnaissance Orbiter. This follows the loss of two previous missions, Mars Observer in 1993 and Mars Climate Orbiter in 1999, which both carried the Pressure Modulator Infra-Red Radiometer (PMIRR) on which MCS is based. The earlier models of PMIRR were built at Oxford, in the USA, and in Russia, and were based on the ISAMS instrument (section 1), developed originally for Earth observation from satellites. The new MCS instrument will address the same scientific goals, the measurement of temperature, dust and humidity profiles on Mars over at least one seasonal cycle, but with a more compact design using new technology. One major use of the data from MCS is in the testing of Martian atmospheric models, as described in Section 5. The models may in turn play a role in the analysis of spacecraft data through assimilation techniques.

Galileo mission to Jupiter

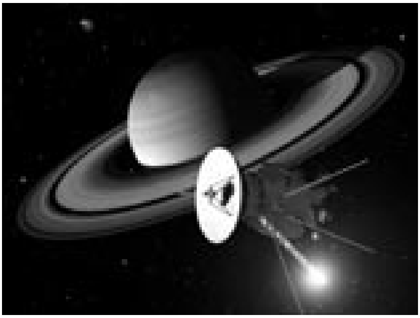
We are part of a team that has developed an imaging spectrometer to map cloud structure and condensable species (water, ammonia and phosphine) in Jupiter's atmosphere, as part of the Galileo mission, launched in 1989. The Galileo Near-Infrared Mapping Spectrometer (NIMS) studied Venus during a 1990 fly-by, providing the first detailed observations of the deep cloud structure and measurements of water vapour and other minor constituents near the surface of the planet. Galileo arrived at Jupiter in 1995 and since then has been returning spectacular data including the first ever in situ measurements of the Jovian atmosphere by the separate Galileo probe. Data from the NIMS instrument have been arriving since 1996. The mission ended (by design!) with Galileo crashing into Jupiter in September 2003.

Sophisticated analysis of the NIMS Jupiter spectra, using multiple-scattering radiative transfer models has already revealed major new findings on the abundance and variability of minor constituents such as water vapour, and on the structure and composition of the clouds which are found to be vertically extended, with the main variable layer responsible for observed visible and visible and near-IR albedo variations found to exist at pressures around 1 bar. This is deeper than the expected level of ammonia cloud deck of 0.7 bar for a solar composition atmosphere and suggests either that ammonia is considerably more abundant than was first thought, or that the ammonia ice is modified from its pure form either by photolysis, reaction with photochemical products or coating/mixing with photochemically produced haze particles. There is in fact evidence for a combination of both these effects. In addition, further analysis continues to reveal new detail of the spatial variability of composition and cloud around such features as the Great Red Spot, White Ovals and Belt/Zone boundaries. A major source of uncertainty in the analysis of the NIMS spectra is the current poor knowledge of the complex refractive indices of ammonia ice, and other Jovian cloud constituents such as ammonium hydrosulphide. A collaboration is thus currently under way with the Jet Propulsion Laboratory to re-measure these in the laboratory under more representative Jovian atmospheric conditions. In addition work is in progress to assess what effect non-spherical particle shapes might have on the modelled spectra.

Cassini-CIRS experiment for Saturn and Titan atmospheres

Our group built the cooler and focal plane assembly for the Composite Infra-Red Spectrometer (CIRS), launched on the Cassini Saturn orbiter in 1997. CIRS will be used to investigate the chemistry, thermal structure and dynamics of the atmospheres of Saturn and Titan when it arrives in 2004. The science team, led by Goddard Space Flight Center, also includes scientists from the USA, France and Germany.

Cassini made a fly-by manoeuvre past Jupiter in December 2000, and the flight instruments were turned on to record the encounter. The use of cooled detectors allowed us to use a much higher spectral resolution and smaller field of view than the similar IRIS instruments which were flown on both Voyager spacecraft, and which led to much of our current understanding of Jupiter's atmosphere. The small (273 microrad) CIRS field of view is necessary to allow us to make limb observations of Saturn, but it also meant that our spatial resolution during the Jupiter fly-by was comparable to Voyager despite the large distance from the planet. We were also able to obtain very good signal to noise ratios for composition measurements, because of the long integration times possible during the approach phase. Some of the data were lost because of problems with the spacecraft near closest approach but we were still able to record a large number of valuable spectra and global spectral maps. We are currently analysing these data to map temperature structure, hydrocarbon abundances, ammonia abundance, phosphine abundance, isotopic ratios of nitrogen and hydrogen, and to search for carbon dioxide remaining after the Shoemaker-Levy collision.



Cassini approaches Saturn in July 2004

Rosetta comet rendezvous

Oxford is part of a consortium (with groups in Rome, Paris and Berlin) selected by ESA to develop a spectroscopic experiment to study the nucleus and core of a comet as part of its comet rendezvous mission, Rosetta. The mission was launched in March 2004 on an Ariane 5 rocket and Rosetta will rendezvous with Comet Churyumov-Garasimenko in 2014

3 Climate dynamics

M R Allen, S R Lewis.

The Climate Dynamics group studies the large-scale behaviour of the atmosphere-ocean system and how it responds to external drivers such as the increases in greenhouse gas levels responsible for anthropogenic climate change. At present, this large-scale response to external forcing appears to be remarkably simple and predictable in even the most complex climate models, despite the chaotic and unpredictable behaviour of many of their individual components. We are interested in understanding the origins of this ‘emergent simplicity’ and assessing the extent to which we should expect it to be shared by the real world. The ultimate objective is to understand the physical constraints on the large-scale climate system in order to place bounds on future climate change.

We are interested in timescales of years to centuries, much longer than the limits of predictability of atmospheric weather systems. Much of our research therefore focuses on how the statistics of atmospheric and oceanic ‘weather noise’ interact with more slowly-evolving aspects of the system, such as the large-scale ocean circulation. On the technical side, therefore, we are interested in the behaviour of random and chaotic systems and particularly methods of model-data comparison in systems supporting widely disparate timescales. Most of our work is carried out in close collaboration with the Met Office’s Hadley Centre for Climate Prediction and Research and we also have very close links with the Atmospheric Sciences Division of the

Rutherford Appleton Laboratory.

Specific current projects include: quantitative attribution of recent climate change, work which has been fed into the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC); exploiting the emerging signal of anthropogenic climate change to quantify uncertainty in multi-decade climate forecasting; ensemble techniques for probabilistic climate forecasting, running multiple versions of the Hadley Centre's climate model on personal computers volunteered by businesses and the general public around the world; interannual climate predictability, concerning the mechanisms responsible for the maintenance and decay of predictability in the atmosphere-ocean system on seasonal to interannual timescales, particularly in mid-latitudes.

In collaboration with the Open University, the Rutherford Appleton Laboratory, the University of Reading and the Met Office, as well as Tessella Scientific Software Solutions, the climateprediction.net project was launched to the public in September 2003. By distributing tens of thousands of unique versions of the Met Office climate model, HadCM3, to the general public worldwide to run on their home, school and work computers, the group hope to produce the most complete probability-based forecast of 21st century climate to date. The experiment, which will run until 2006, investigates the uncertainties inherent in climate models, due to the uncertainties in model parameterisation schemes and initial conditions. Different scenarios for future greenhouse gas emissions, volcanic activity, etc are also being investigated. The results of the experiment should give policy makers a more complete scientific base for planning to deal with the consequences of climate change.

4 Modelling of the Earth's atmosphere

D G Andrews

We use a range of computer models of the atmosphere, in conjunction with a wide variety of data sets (including the sub-department's large data sets on the stratosphere and mesosphere), to help understand the dynamics and physics of the observed troposphere, stratosphere and mesosphere, thus leading to an improved understanding of the processes which influence weather and climate.

Our modelling work is in collaboration with the UK Universities' Global Atmospheric Modelling Programme, the Met Office, and several European groups. Some of the models we use are quite simple, while others include very detailed representations of fluid dynamics, radiative processes and chemical transport.

We are currently studying several aspects of the large-scale atmospheric circulation, including the processes responsible for the annual and quasi-biennial oscillations in the equatorial stratosphere, the effects of soil moisture on the predictability of African rainfall, and the impact of changing solar irradiance on the climate system. We also study the transport of chemical constituents such as water vapour in the lower stratosphere and the transfer of mass through the tropopause. We have long-standing interests in atmospheric wave motions, which play a crucial role in many of these processes.

Work is also being done on fundamental aspects of data assimilation. This is the process by which diverse observations are combined with sophisticated numerical models to produce an optimal estimate of the current atmospheric state. The aim is to gain a better understanding of how known physical properties of the dynamical equations can be combined with observations in a robust and reliable way.

5 Atmospheric modelling of other planets

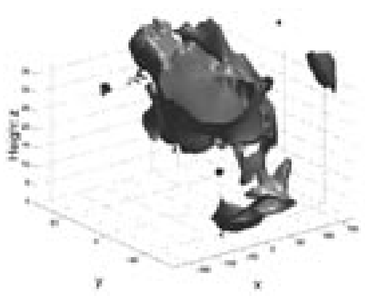
P L Read, S R Lewis

In parallel with our involvement in observations of Venus, Mars, Jupiter and Saturn, we are actively modelling dynamical processes relevant to phenomena in the atmospheres of the terrestrial and major planets, with particular emphasis at present on the atmospheres of Mars and Jupiter. Such studies are needed for the interpretation of existing and future data (e.g. from NASA's Galileo and Cassini missions and Mars programmes, see section 2). They also help in the planning of new observational programmes. Current activities include the detailed simulation of the atmospheric circulation and climate of Mars, assimilation of new observations of Mars and the development of simpler process models of large-scale jets and eddies on Jupiter and Saturn. In future we plan to extend the range of planets modelled to include Venus, following the development path of the Martian GCM, but for an even more challenging atmosphere.

The Mars General Circulation Model, developed in collaboration with the Laboratoire de Météorologie Dynamique in Paris, attempts to include the main variables which govern the Martian weather and climate system. Discrepancies with observations will reveal new processes at work, or an incomplete understanding of the old ones. Benefits of this work, in addition to a better scientific understanding of the physics of atmospheres, will be prediction of climatic conditions which may affect future landings and the possible location of water reservoirs on Mars. A fully-tested climate model for modern Mars also provides a starting point for understanding how the planet may have changed from its warm, wet past to the present austere conditions. On shorter timescales there is evidence of less dramatic climate change, in the form of polar layered terrains, and the model is being used to begin to investigate the processes which may give rise to this.

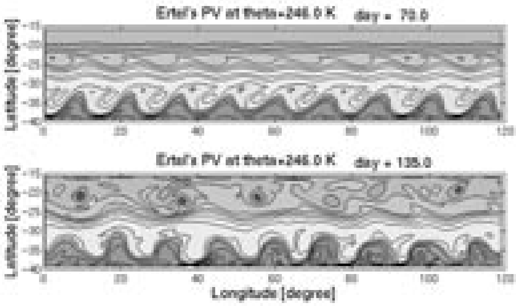
Until the recent advent of mapping phase data from the Mars Global Surveyor (MGS) mission, atmospheric data from Mars lacked both spatial and temporal coverage. New remotely sensed observations have already greatly extended this coverage, both spatially and over the seasonal cycle. Atmospheric sounders only allow the retrieval of certain variables, such as temperature over a limited altitude range, and GCMs will be of great use in the analysis and interpretation of such data, both through direct comparison and more sophisticated data assimilation techniques. Carefully validated GCMs also provide the best means of predicting the Martian mean climate and its variability in regions, or for atmospheric variables where few, if any, observations exist.

Recent developments with the Mars GCM have included raising the top of the model to the lower thermosphere (above 120 km), the inclusion of detailed modelling of the processes of dust lifting, advection and deposition (see the example of a simulated dust storm in the figure) and the inclusion of processes needed to model the modern-day Martian water cycle.



Three-dimensional dust structure shown by the $1.5\text{x}10^{-5}$ kg/kg dust mixing ratio isosurface 12 days after the beginning of the simulated Chryse storm, see previous figure. The ‘x’ axis shows degrees east longitude, and the ‘y’ axis degrees north latitude.

A numerical model is under development to enable simulation of the circulation of the upper tropospheres and stratospheres of Jupiter and Saturn. This model is derived from the Met Office’s Unified Model of the Earth’s atmosphere, which has been employed for both operational weather forecasting and climate research, with the aim of including realistic representations of a range of physical processes in order to improve our understanding of the role of various dynamical phenomena and thermodynamical processes on the large-scale circulations of the gas giant planets. So far, the model has primarily been used to investigate the basic mechanisms that support the complex yet coherent structures of the observed Jovian winds such as the Great Red Spot, White Ovals and alternate multiple jets. The resulting model will eventually be capable of comparatively realistic simulation of atmospheric circulations, and will ultimately be of great value in the interpretation of current and future observations of Jupiter and Saturn, e.g. from the Galileo and Cassini missions.



Evolution of initially parallel unstable jets in a channel version of the GCM

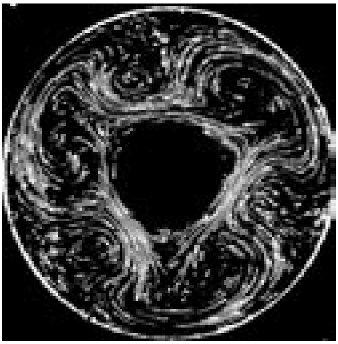
6 Laboratory fluid dynamics

P L Read

We use laboratory systems and a complementary range of numerical models to study the behaviour of circulations and instabilities relevant to oceanic and atmospheric flows. Experiments are typically carried out in rotating containers with either differential heating or mechanical forcing, to obtain analogues of large-scale circulations in atmospheres and oceans. The laboratory systems provide a means of studying geophysically-relevant dynamical processes under controlled conditions, both in their own right and as test beds for ideas and techniques applicable to the interpretation and simulation of atmospheric and oceanic phenomena.

Recent projects have investigated the highly nonlinear development of baroclinic and barotropic instabilities (which are responsible for the formation of large-scale weather systems on the Earth, Mars and other planets), their effects on the transport of heat, momentum and other tracers, their influence on the predictability of the flow, and the ability of numerical modelling techniques to simulate their behaviour. These instabilities exhibit a wide variety of routes to chaotic behaviour and geostrophic turbulence, and we are leaders in the application of ideas and techniques from dynamical systems theory to the analysis, interpretation and modelling of flows in experimental systems.

Current and future studies are being directed towards investigating the nonlinear effects of time-varying boundary conditions (analogous to the effects of seasonal and other cycles in external forcing on the Earth's climate) on baroclinic circulations, and mechanisms for the breakdown of spatially-ordered flows from chaotic behaviour to fully-developed turbulence — arguably one of the last great unsolved problems of classical physics.



Streaks from the motion of tracer particles in a thermally-driven, rotating annulus. The flow shows a complex wavenumber 3 pattern of baroclinic waves.

ATOMIC AND LASER PHYSICS

Professor Ian Walmsley

Research in the department involves some of the most rapidly developing areas of physical sience, studying novel states of matter at extreme ranges of temperature, laser-produced plasmas under extreme nonequilibrium conditions, highly nonclassical quantum phenomena using atoms and photons, and precise spectroscopy using extremely stable broadband lasers and quantum optics. The work in these areas has broad implications for physics, ranging from new approaches to computation based on quantum mechanics to novel schemes for particle accelerators based on laser plasmas. Indeed, there are consequences for the technology of the future, from improved global positioning systems to completely secure optical communications systems.

The main research thrusts are focused in the following areas:

Ultracold matter: The study of mesoscopic quantum states of matter in the regime where the de Broglie wavelength of the atoms is comparable with their spacing, giving rise to quantum phase transitions such as those associated with Bose condensation and superfluidity. The precision with which these phase transitions can be engineered, using stabilized lasers and designer electromagnets, enables the detailed studies of many-body phenomena normally associated with condensed matter, and allows these states to be exploited for applications.

High-intensity laser-matter interactions: The extremely high peak intensities associated with modern short-pulse laser systems can produce electric fields greater than those binding valence electrons in atoms. The behaviour of matter under such extreme, yet transient, conditions gives rise to highly nonlinear phenomena, such as the generation of XUV and X-ray radiation. The novel light sources so produced can be used to study the dynamics of a vast range of matter, as well as its structural changes, on unprecedented timescales.

Quantum and nonlinear optics: The interaction of light and matter at the quantum level, especially using laser pulses of extreme brevity, with durations in the femto and even atto seconds regime, opens up new ranges of phenomena associated with the timescales of internuclear motion in molecules and electronic motion in atoms and on surfaces. These interactions can be used not only to probe atomic and molecular dynamics, but also to control them. Non-classical optics is also applied to fundamental studies of the structure of quantum mechanics, and its implications for quantum enhanced communications and metrology.

Quantum information processing: The Centre for Quantum Computation concentrates both on harnessing the power of quantum physics for computing and cryptography, and on understanding the implications of information theoretic ideas for quantum mechanics. The enormous potential for increased capacity for information processing requires both complex protocols for combating decoherence, and robust control of individual atoms and ions, as well as their collective excitations. The precise manipulation of trapped atoms and ions, are key technologies that are exploited in building prototypical quantum processors.

Within these themes there is a range of experimental and theoretical activity, as well as broad overlap between the areas. Many faculty work in more than one area, and there is strong exchange of ideas and of expertise in interactions between groups. In short, we cover the ultracold, ultraintense, ultrafast and ultraweird, using a gamut of cutting edge technologies.

1 High-intensity light-matter interactions

In the Centre for Ultrafast X-Ray Science, we use some of the most powerful lasers in the world to investigate a variety of phenomena that occur in intense laser-matter interactions. The most recent advances in laser science are making available focused intensities greater than 10^{20} W/cm^{-2}, which transform matter into plasma and create extreme non-linear effects by causing the electrons to oscillate at relativistic velocities. There are many new scientific applications including the development of X-ray lasers, laser-driven particle accelerators, attosecond XUV sources, femtosecond X-ray diffraction, and the study of astrophysically relevant material in the laboratory.

The Centre has its own high-power (3 TW) femtosecond laser facility in the Clarendon Laboratory, but also makes extensive use of EPSRC facilities at the nearby Rutherford Appleton Laboratory and powerful lasers in the USA and Europe.

1.1 Laser-driven particle accelerators

S M Hooker, J S Wark

When an intense laser pulse propagates through a plasma, electrons are pushed away from the front and back of the pulse leading to the formation of a longitudinal plasma wave that propagates at the group velocity of the optical pulse. The longitudinal electric field in the plasma wave can be as high as 100 GeV m^{-1}, more than three orders of magnitude larger than that found in conventional RF accelerators such as those used at CERN. Particles injected into the correct phase of the plasma wave can be accelerated to energies of order 1 GeV in only a few tens of millimetres (compare this with the rest mass of the electron which is only 0.5 MeV). This 'laser wakefield accelerator' is particularly promising for generating beams of short pulse, high-energy electrons for applications in femtosecond electron diffraction, medical imaging, and miniature free-electron X-ray lasers.

The successful implementation of laser-driven accelerators requires the driving laser pulse to be guided over tens of millimetres. However, the laser-plasma interaction length is fundamentally limited by diffraction to distances of order the Rayleigh range, which for spot sizes of a few tens of μm is only a few millimetres. Refractive de-focusing often restricts the interaction length still further. We have recently developed a new type of waveguide which is able to overcome such de-focusing.

The guiding technique developed by the group is ideally suited to the development of wakefield accelerators, and consequently we now play a key role in a UK-wide collaborative research programme to investigate controlled laser-driven acceleration of electrons and the prospects of using the high-energy electron pulses to drive free-electron lasers operating at X-ray wavelengths. In the course of this project we will develop waveguides tailored to the optimal conditions for acceleration and investigate plasma channels with longitudinal structure to assist phase-matched acceleration. We will also take part in a number of collaborative experiments on guiding of relativistic laser pulses, and laser-driven acceleration.

1.2 X-ray lasers

J S Wark, S J Rose, S M Hooker, K Burnett

XUV laser beams of high directionality and coherence can be generated in a medium of laser-heated plasma created using a multi-terawatt laser. Currently the group is investigating methods of creating such lasers by photopumping, where X-ray emission from one hot plasma (for example the resonance lines of hydrogenic ions) pumps transitions in a separate laser-produced plasma. In addition, within the next few years free electron X-ray lasers, with wavelengths of 0.1 nm, will be built based on linear accelerator technology. The brightness of these lasers will be many orders of magnitude greater than current synchrotrons, producing ultra-bright pulses of X-rays of femtosecond duration that will have a significant impact on both the life and physical sciences. The group is also developing theoretical models of how such novel radiation interacts with matter.

Several mechanisms are being studied for controlling the ion species and electron energy, both of which strongly affect the population inversions available for short wavelength via either collisional excitation or electron-ion recombination. In combination with the waveguides developed in the Center, this may allow us to greatly increasing the output energy of XUV lasers, and allowing lasing to be achieved on many new laser transitions. In the first experiment of its type, we recently demonstrated lasing at 41.8 nm on a transition of Xe8+ driven by optical field ionization in a gas-filled capillary discharge waveguide.

In parallel, we are developing new theoretical methods to treat electron correlation effects in intense laser fields. This work is aimed towards the development of new coherent sources of X-rays. Of particular interest at the moment is the way intense field processes occur in rare-gas clusters. This is a field in which rapid developments are occurring and we are providing theoretical modelling and advice for several experimental groups at Oxford and Imperial College, London.

1.3 Radiation transfer

J S Wark, S J Rose

When high-power lasers interact with a target, they create plasmas at extreme conditions. The velocities of the ablating plasma can easily reach a few percent of the speed of light, with accelerations in excess of 10^{15}g. The flow of radiation through such rapidly expanding plasmas is of great interest, as the pertinent physics is the same as that which occurs during supernovae explosions. Thus the group is involved in a number of experiments to measure such effects, comparing the results with both laser-plasma simulations, and with the results of codes used in the Astrophysical community. Astrophysically-relevant plasmas can also be produced using our small in-house laser, where measurements are made of the spectra and equation of state of strongly-coupled plasmas.

1.4 Femtosecond X-ray diffraction

J S Wark

X-ray diffraction can yield direction information on the distribution on electron density within matter. Over the last few years novel sources, based on both synchrotrons and lasers, have led to the capability to obtain diffraction information on femtosecond timescales. In principle, such technology could lead to the creation of 'molecular movies'– i.e. the observation of the flow of electron density during chemical reactions. The group has been one of the leading innovators in this field, using such novel sources to probe atomic motion on picosecond and sub-picosecond timescales. Experimental work utilises lasers in both the UK and the US, as well as the bright synchrotron sources at Berkeley and Grenoble, and has to date concentrated on the investigation of coherent phonons, the response of matter to shock compression, and femtosecond X-ray switches.

2 Ultracold Matter: Bose-Einstein condensation and atom optics

It has recently proved possible to produce Bose condensed assemblies of trapped atoms. These ultracold objects, with temperatures in the range μK – nK, have fascinating properties that we are just beginning to explore. Part of this work involves the study of how these macroscopic quantum objects respond to external electromagnetic probes. These studies are closely linked to the experimental work at Oxford and elsewhere. The other main subject of our research in this area is the study of 'atom-lasers' and non-linear atom optics. This could also be termed coherent matter wave physics. In this we are constructing theories of matter wave amplifiers. These are the analog of the light amplifiers used to produce a laser. This work is at the interface between quantum optics and condensed matter and has developed in a very exciting way in the last year or so.

2.1 Superfluidity of a Bose-condensed gas

C J Foot, K Burnett, D Jaksch

Techniques for laser cooling and trapping of atoms have enabled the phenomenon of Bose-Einstein condensation to be observed in a gas of weakly interacting atoms and this system offers an exciting range of new experimental opportunities. We have concentrated the superfluid properties of the condensate such as the creation of vortices in a rotating trap and observations of the so-called scissors mode (a form of quadrupole oscillation that involves irrotational flow). In contrast to the situation in superfluid helium, the properties the weakly interacting system can be calculated from first principles and we will make comparison with the predictions made by Professor Burnett's theory group. In the future, we will modify the existing magnetic trap to produce toroidal samples of Bose-condensed gas and make observations of the quantized superfluid flow around the ring. The experimental observation of the properties of BEC in different geometries promises new insights into this intriguing system.

2.2 Quantum states of atoms in optical lattices

C J Foot, K Burnett, D Jaksch

An optical lattice is formed by standing waves of light that create an array of potential wells for the atoms e.g. an 'egg-box' shaped potential at the intersection of two orthogonal standing-waves. Atoms loaded from a Bose-condensate into a three-dimensional optical lattice, under carefully controlled conditions, form a quantum state with exactly one atom per well i.e. not just one atom on average but a state with an extremely small probability of having zero, or two atoms, at any site. This is the initial state required for quantum computation with neutral atoms and our first aim is to study this system's properties in order to assess its potential for this application. The quantum information is effectively processed by the array of atoms as they interact and develop entangled many-particle states. Theoretical modelling of the expected behaviour is being carried out (as described under Coherent Matter Wave Group in section 1) and various experimental techniques for controlling the interactions between pairs of atoms will be tested.

2.3 Atom optics and quantum chaos

K Burnett, C J Foot

The ability to control the momentum and position of cold atoms through optical means has generated much interest throughout the world in the last ten years. At Oxford we have developed a new approach which allows atoms to be coherently accelerated to velocities more than one hundred times greater than has been available with previous methods. In our technique, atoms are accelerated by a pulsed standing light wave in a process which is roughly analogous to pushing a child on a swing. If the pushes are timed correctly the child can gain momentum with each push.

There is a close link between these atomic 'accelerator modes' and a system which exhibits chaos called the delta-kicked rotor. Thus in addition to applications in atom optics our experiments with pulsed standing light waves allow us to study quantum chaos.

3 Quantum Information Processing

The discovery that quantum physics allows fundamentally new modes of information processing has required the existing theories of computation, information and cryptography to be superseded by their quantum generalisations. The Centre for Quantum Computation conducts theoretical and experimental research into all aspects of quantum information processing, and into the implications of the quantum theory of computation for physics itself.

3.1 Theory Group

D. Jaksch, A Steane, K Burnett, D Deutsch, E Kashefi, I Fuentes-Guridi

Faculty in the theory group concentrate on the physics of information. In general terms, we study the nature of information encoded in quantum states, focusing especially on phenomena such as quantum entanglement and interference in the context of new modes of computation and communication.

In particular, work is underway to develop schemes for implementing quantum computing devices in quantum optical setups. Quantum optical techniques allow accurate control of the coherent evolution of quantum systems, and therefore provide several promising candidates for the implementation of quantum logic including trapped ions, cavity QED and neutral trapped atoms. Experimental advances in placing Bose-Einstein condensates in optical lattices makes them attractive candidates for novel schemes for quantum logic. We are specifically interested in devising scalable quantum computing schemes that are unaffected by the most dominant sources of errors like stray magnetic fields and fluctuations in laser intensities, and allow efficient processing of quantum information, i.e., gate operation times much shorter than any decoherence time scale of the system.

However, since we cannot expect the realization of a universal quantum computer within the near future we are also studying quantum optical systems that could be used for special purposes in quantum information processing like quantum simulations of physical systems or building blocks for implementing quantum communication protocols. It is very likely that these studies of multi-particle entanglement will also give important insights into the nature of the condensation process. This is being studied e.g. as a way to produce the optimally coherent source of matter waves. This will provide a strong basis for continuing exchange between the two areas.

3.2 Experimental Ion Trap Quantum Computation Group

A Steane, D Stacey, D Lucas

Experimental methods in atomic physics and quantum optics are currently among the most precise available in science. It is now possible to manipulate and measure single atoms, or small groups of atoms, by first confining them by electromagnetic potentials — making a so-called atom or ion 'trap'— and then illuminating them with pulses of laser light of controlled frequency and duration. The importance of the ion trap for quantum information processing is that it is the only method which allows complete control of an isolated several-qubit quantum system using current technology. Individual ions can be probed and re-set at will, which allows active stabilisation of the system by probing for errors and correcting them. We have recently built and are currently running such a device. The major research aims are to demonstrate new methods which we have proposed to probe the quantum states, and to achieve quantum processing among the ions, especially quantum error correction. We aim to study open questions in the fundamental theory of quantum computing, going beyond basic demonstration experiments

3.3 Experimental Nuclear Magnetic Resonance (NMR) Quantum Computation

J A Jones

Liquid state NMR is currently the leading technology for implementing small quantum computers: although there are formidable problems in scaling up NMR systems to build large quantum computers it remains a superb system for developing basic techniques and performing proof of principle demonstrations. We exploit the nuclear spins in a small molecule to represent quantum information, and the NMR information processor uses a large ensemble of such computers in solution. In 1997 we demonstrated the first experimental implementation of a quantum computer by performing Deutsch's algorithm on a two qubit NMR quantum computer. Since that time many other algorithms, including Shor's quantum factoring algorithm, and protocols, such as quantum teleportation and quantum cloning, have been implemented. We are currently investigating techniques for implementing precise quantum logic gates in the presence of experimental errors, and the use of para-hydrogen to prepare ultra-cold spin systems. Theoretical aspects of our program are carried out at the Centre in conjunction with the theory group; experiments are performed on a brand new 600 MHz NMR spectrometer which we share with groups in Chemistry and Plant Sciences.

3.4 Experimental Photonic Quantum Information Processing

K Banaszek, I A Walmsley

Quantum cryptography, communications and computation can all be implemented using photons as qubits. As with other forms of quantum technology, the key feature that enables the enhanced capability is entanglement, and a large part of our effort is directed toward the design and implementation of sources of entangled photon multiplets. These are applied not only in enhancing the capacity of classical communications channels, but also to the demonstration of elementary protocols out of which quantum logic elements can be constructed. Quantum states of light are prepared via conditional detection by means of spontaneous scattering processes that generate photons in pairs, so that the detection of one member of the pair leaves the other in a pure states. We have recently combined standard nonlinear optical methods with microstructured materials and modelocked lasers to generate the highest yet correlation between single photon states.

4 Quantum and Nonlinear Optics and Laser Spectroscopy

The interaction of light and matter at the quantum level provides important insights into the dynamics and structure of atoms and molecules. Indeed, the boundary between the quantum and classical worlds has perhaps been explored most deeply in optics: the ideas of local realism, entanglement and interference are all amenable to test within this paradigm. Research in the Institute of Experimental Photonics and the Oxford Institute for Laser Science covers a broad range of linear and nonlinear frequency and time resolved spectroscopy. Nonlinear optics occurs when the response of matter to an applied light field is nonlinear. Such interactions have both fundamental and technological importance. For example, broadband modelocked lasers generating frequency "combs" are applied to testing fundamental physical theories such as QED. Nonlinear optics, using broadly tunable narrowband lasers, is employed for the detection of trace species in gases. And quantum optics, using both kinds of lasers is used to explore the nature of local realism in physics, and simultaneously developing technologies that harness entangled photons to provide more sensitive and precise measurements of macroscopic objects.

4.1 Ultrafast Optics and Attoscience

I A Walmsley

Nonlinear optical interactions are generally used to shift the frequency of or add frequencies to a pulse of light. In the most extreme cases it is now possible to add sufficient bandwidth to an input pulse that the output pulse has a duration of 10-19 seconds. This extraordinary brevity, and the short wavelengths necessary to produce such pulses, are beginning to open up a new regime of dynamical studies in which it will be possible to view time-dependent structural changes in solids and large molecules. This work is part of the UK Attoscience Consortium, led by Imperial College, whose aim is to develop sources and metrology for applications involving the study of ultrafast dynamics.

The major projects in the ultrafast group in this area revolve around the need to correctly characterize the temporal field (rather than simply the intensity) of the pulse in order to properly unravel the interactions that take place in the nonlinear media. Recent successes include the development of a method to measure the entire spatio-temporal field profile of a sub-two-cycle optical pulse, the study of nonlinear space-time coupling, and a proposal of a scheme to measure the temporal structure of an attosecond X-ray pulse. The techniques developed in this set of activities impact several other areas of the group's research, including the ability to manipulate and characterize pulses used in the atomic and molecular control experiments, for example.

4.2 Coherent Control of Atoms and Molecules

I A Walmsley

One of the most fascinating developments of the past decade has been the ability to manipulate matter at the quantum level – that is to place it in states that are suited for a particular purpose, be it the study of ultracold Bose-condensed material, the application to nanoscale lithography or observing and controlling molecules undergoing chemical changes.

Two projects underway in the ultrafast group in this area involve the development of quantum logic in diatomic molecules, and their operation in a noisy environment, as well as the study of binary collisions leading to the formation of ultracold molecules from optically cooled and trapped, ultracold atoms.

These projects require the application of methods of learning control to optimize the generation of specific target states in molecules. This involves preparation of ultrashort optical pulses with specific field patterns, and their interaction with prepared samples of ultracold atoms or hot molecules.

4.3 Non-linear laser spectroscopy

P Ewart

We develop novel non-intrusive and remote sensing techniques for molecular spectroscopy and chemical physics applications. Our theoretical studies have revealed subtle quantum interference effects arising from the interplay of random fluctuations of the incident fields and atomic relaxation. This work helps us understand the complex effects of laser modes and field statistics in non-linear spectroscopy.

Molecular spectra can be recorded using DFWM with frequency-scanned narrow line-width lasers yielding high-resolution spectra from which accurate molecular parameters may be deduced. The methods of non-linear spectroscopy using DFWM, polarization spectroscopy and cavity ring-down spectroscopy are being extended to the mid-infra red spectral region for the detection of hydro-carbon species important in combustion, plasma and atmospheric chemistry. A major aim of the present work is to extend high-resolution non-linear techniques to the spectroscopically rich infra-red region where many important hydrocarbon molecules have their ‘finger-print’ spectra.

The group is involved in collaborative research programmes in combustion diagnostics with Dr Richard Stone in the Department of Engineering Science and two major centres in Germany: the Institute for Technical Combustion, University of Stuttgart and the Physical Chemistry Institute, University of Bielefeld. These collaborations, especially the former, are concerned with the development of optical diagnostics of internal combustion engines using nonlinear spectroscopy with the aim of improving fuel-efficiency and reducing pollution.

A further collaboration is underway with Dr Derek Terrar in the Department of Pharmacology in Oxford to study laser induced fluorescence of Ca+ ions in biological systems. This work aims to study the dynamics of muscle contraction by using fibre-optic delivery systems and fluorescence microscopy to trigger specific sites within individual muscle cells. The technique is used to study effects of drugs on spontaneous and induced triggers of particular relevance to heart disorders.

4.4 Tests of discrete symmetries using lasers

P E G Baird

Sensitive laser techniques in atomic physics can be exploited to look for violations of the discrete symmetries: parity (P), charge conjugation (C) and time reversal (T). In particular, experiments sensitive to P-, PT-, T- and CPT-violations are possible and provide tests of fundamental physical theories. Violation of P-symmetry is connected with tests of electroweak theory while tests of any PT- or T-violation can be related to CP-violation detected in neutral kaon decay. The experimental techniques can involve optical polarimetry, spectroscopy, optical pumping, trapped atoms and interferometry.

New experimental possibilities are under consideration and some related theoretical work is undertaken. Of particular interest are the recently developed coherent frequency combs that make use of mode-locked lasers and optical fibres. These have opened up the possibility of unprecedented absolute frequency measurements throughout the optical region, and new experiments on excited states of atomic hydrogen, especially the so-called circular states, are being undertaken in collaboration with the National Physical Laboratory.

4.5 Studies of highly ionized atoms

J D Silver

Highly ionised atoms are important constituents of very hot objects, such as stars, or Earth-bound thermo-nuclear fusion plasmas. People study highly charged ions for a number of rather different reasons. If, for example, you would like to understand what goes on in a star, or indeed what might go on in a fusion reactor on Earth, then it makes sense to generate the sort of ions which are encountered in these environments, and then study their properties. These properties include the atomic spectra of the ions, and collisions and radiative processes. Once these properties are sufficiently understood, you might then fly a satellite with a suitable X-ray spectrometer on board pointing at the Sun, record the X-ray spectra of highly charged ions excited in a solar flare, and then deduce from your measurements important parameters such as the temperature and electron density in the flare. Such information might then give you more information on how the Sun ‘works’. Another field where highly charged ions play a crucial role involves the quest for a useful X-ray laser. The ‘laser medium’ of an X-ray laser is some species of highly ionised atom. An intimate knowledge of the atomic structure and excitation and de-excitation phenomena for specific highly ionised atoms is therefore required to gain a proper understanding of the potential of the schemes for X-ray lasers which are currently being pursued in many laboratories. A collaboration with the Japan Science and Technology Corporation involves work with cold trapped ions both in the area of fundamental atomic physics, and in a new area of nanotechnology. The collaboration links Oxford and the NPL in the UK with the EBIT group at the UEC ILS in Chofu, Tokyo.

CONDENSED MATTER PHYSICS

Dr A T Boothroyd

Condensed matter physics is concerned with understanding, on a microscopic scale, the many and varied properties of condensed matter, and using this understanding to develop new materials with novel properties. This often involves the development of new concepts to describe the collective behaviour of interacting systems. The research in Oxford spans a wide variety of different types of materials: semiconductors, superconductors, magnetic materials, optical materials, and polymers, and uses a wide variety of different techniques: optical, magnetic, electrical, magnetic resonance, neutron and X-ray scattering as well as theory. A new research programme in biological physics is being established which will focus attention on single molecule measurements, and the sub-department is leading a major inter-disciplinary research collaboration (IRC) in bio-nanotechnology where the emphasis is placed on molecular machines, functional membrane proteins, nano-electronics and nano-optics.

There are over 150 members of the Condensed Matter Physics sub-department, of whom 15 are permanent academic staff, and about 60 are graduate students. Most of the experiments are performed in the Clarendon Laboratory although use is also made of neutron scattering facilities at the nearby Rutherford Appleton Laboratory, at ILL in Grenoble and at other European centres, of the synchroton X-ray scattering facilities at the Daresbury Laboratory and at the ESRF in Grenoble, as well as the muon beam at ISIS and the particle accelerators at CERN. Facilities in the laboratory include the highest magnetic fields in the UK, ultrafast femtosecond pulsed lasers, MOVPE equipment for growing semiconducting heterostructures, MBE equipment for growing metal multilayers, and crystal growth facilities for nonlinear optical, magnetic and high-temperature superconducting single crystals. A new facility for bio-nanotechnology is currently being developed in the laboratory. The research programme is outlined in detail below: although it is divided into topics under broad subject headings, there is considerable overlap between topics.

1 Semiconductors

There is a wide-ranging programme of research into the properties of low-dimensional semiconductor structures, including both fundamental and applied properties. Typical structures consist of layers only a few atoms thick; small length scales can be used to ‘engineer’ the material properties, leading to new and exciting effects which may be the basis of the next generation of electronic and optoelectronic devices. The work carried out covers the growth of new materials, fabrication of these into nanoscale quantum dots and wires, and studies of the electrical and optical properties of many different structures at extremes of low temperature, high magnetic fields, very high pressures.

Magnetotransport and new states of matter

R J Nicholas

Magnetotransport is studied in very high magnetic fields (60 T) and low temperatures (25 mK) with the aim of studying the new states of matter which can occur for interacting electrons. The application of large magnetic fields causes total quantisation of the electron energy levels, leading to phenomena such as the quantum Hall effect, fractional quantum Hall effect, and Shubnikov-de Haas oscillations. New states of matter form, such as the Wigner solid and the quantum liquid formed from composite fermions which causes the fractional quantum hall effect. When holes are added to the system then bound electron-hole pairs (excitons) form and the system may show Bose-Einstein condensation, leading to a Bosonic insulator state. Heterostructures made from GaSb/InAs are used to study electron-hole systems, where both carriers can exist simultaneously and a variety of electron-hole coupling effects have already been observed.

Superlattice (vertical) transport is being studied in short period structures made from GaSb/InAs where minibands can be designed to give a variety of resonant quantum transport processes which cause negative differential resistance, Stark cyclotron resonance and novel magnetoresistance. These structures are being designed with the object of producing quantum cascade lasers operating the TeraHz spectra region.

Magnetotransport measurements are routinely performed at magnetic fields in excess of 50 T, using the new pulsed magnetic field laboratory and with our new 21.5 T superconducting magnet. Electron beam lithography and AFM is used to produce 'quantum wires' and 'quantum dots' in several material systems, and these are studied using both transport and capacitance techniques.

Electrical transport studies of carbon nanotubes which are doped or filled with a range of different materials is just beginning in a new joint project with the Department of Materials. This involves manipulating and contacting the tubes using a combination of e-beam lithography and AFM.

Far-infrared spectroscopy

R J Nicholas

Far-infrared spectroscopy in the region of mm to micron radiation is used to observe cyclotron resonance of electrons and holes in magnetic fields to study their effective masses. This is used to study quantum liquid states at low temperatures and to search for Bose-Einstein condensates. The new technique of optically detected cyclotron resonance has been developed to study undoped materials.

Interband spectroscopy, Skyrmions, nanotubes and interacting electrons

R J Nicholas

Optical transitions occur between the confined energy levels of electrons and holes, leading to sharp 'interband' absorption and emission peaks. These are studied in magnetic and electric fields to determine the properties of excitons, electrons and holes, and to relate these to the new band structures formed in superlattices and quantum wells. The properties can then be used in the 'design' of new materials. Magneto-optical measurements can now be made up to 60 T. Wide band gap materials being developed for use as blue and UV lasers such as GaN, ZnS and II-VI superlattices are being studied. These materials are very polar and have very large exciton binding energies which can dramatically alter their optical emission processes and couple all of the carriers very strongly.

Strongly spin polarised states are formed at very high fields, and a search is being made for new 'Skyrmion and composite Skyrmion' particles in strongly interacting gases of 2-dimensional electrons in high mobility GaAs/GaAlAs heterostructures. High pressure and quantum well width are used to design materials with zero g-factor to enhance the likely occurrence of the new textured spin states. The structures are studied using polarized reflectivity, photo-luminescence and FIR modulated photoluminescence.

Carbon nanotubes often act as semiconductors, depending on their symmetry and diameter. Research is being performed to investigate the optical properties of the nanotubes and how these can be modified and controlled by filling the tubes with electrically active materials. High magnetic fields are being used to attempt to modify the electronic phase around the tubes and to observe possible Aharoniv-Bohm effects. Strain is applied by environmental changes which can be used to characterise the tubes. A search is being made for excitonic effects.

THz time-domain spectroscopy

M B Johnston

The terahertz (THz) band of the electromagnetic spectrum is defined as the range of frequencies between microwaves and mid-infrared light, and hence covers the region where electronic and optical technologies merge. THz photons encompass the characteristic energies of many physical processes. In condensed matter systems lattice vibrations (phonons), collective motion of charge (plasmons), and exciton binding can all be observed using THz spectroscopy.

Recently, femtosecond laser pulses have been used to generate extremely broadband (100GHz to 30THz) single-cycle THz pulses. These pulses can be detected coherently with very high sensitivity, and may be used for time-domain spectroscopy experiments on a variety of systems. Importantly, the time-domain spectroscopy technique can be extended to study the dynamics of systems with femtosecond time resolution.

Current research centres on using dynamic THz spectroscopy to study intersubband transitions in semiconductor heterostructures. These measurements are important for the design of quantum devices such as quantum cascade lasers and quantum-well infrared photodetectors, which show promise for future high-speed optoelectronic applications. Projects to investigate the time-resolved structural properties of organic semiconductors and macromolecular systems are currently starting.

Organic semiconductors

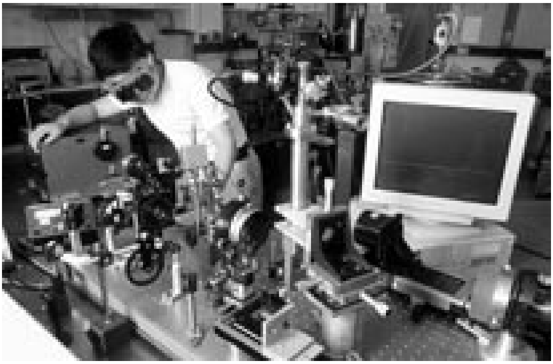
L M Herz

Organic semiconducting polymers and molecules have emerged over the last decade as cheaper and more flexible alternatives to existing semiconductor technology. Light-emitting displays based on these materials are now rapidly approaching commercial standards with international companies having developed a range of prototypes. However, fundamental knowledge is still lacking on how intermolecular interactions in such systems are best tuned in order to optimize the mobility of charge carriers and diffusivity of photoexcitations. One highly promising approach to this problem is through supramolecular chemistry, which offers a wide-ranging toolkit to assemble conducting molecular materials into desired arrangements in solution prior to a casting process.

Currently, a variety of self-assembly strategies are being explored, ranging from supramolecular organization assisted by hydrogen bonding (in collaboration with Prof E.W. Meijer, TU Eindhoven) to encapsulation of conjugated polymers with insulating molecular beads (Dr H Anderson, Oxford Chemistry). Ultra-fast time-resolved photoluminescence spectroscopy is used to gain insight into the fundamental mechanisms involved in photoexcitation transfer processes, and to assess the effectiveness of various self-assembly strategies in creating intermolecular order.

2 Quantum optoelectronics

This research field is concerned with the study of optical processes in condensed matter where the quantum properties of photons and electrons are of central importance. Not only are the electronic band structures engineered, as in low-dimensional systems, but also photonic band structures, as in semiconductor microcavities and microstructured dielectrics. Ultrafast spectroscopy is widely used to probe fundamental electronic interactions in semiconductor nanostructures and devices using femtosecond lasers. Quantum states of light are produced in which photon number and phase fluctuations are reduced below the limit imposed by the uncertainty principle (not both simultaneously!).



View of an alien world – from a quantum dot! – femtosecond laser spectroscopy of semiconductor nanostructures using photon mixing.

Ultrafast spectroscopy of semiconductor nanostructures

J F Ryan

Semiconductor nanostructures such as quantum wires and quantum dots are being investigated using optical techniques which allow the properties of electrons and holes confined in systems of reduced dimensionality to be probed directly. Self-assembled structures such as GaAs v-groove quantum wires and GaAs/InAs quantum dots are of particular interest from a fundamental perspective as well as for their potential device applications, e.g. lasers, single photon sources, and detectors. We are developing techniques to permit interacting quantum structures to be fabricated which will allow the underlying physics of quantum information processing to be investigated.

Scanning near-field optical spectroscopy is currently being used to obtain very high spatial resolution - below the diffraction limit (~50 nm) - which allows dynamical processes in individual nanostructures to be probed. The dynamics of photoexcited semiconductors is being measured on the timescale of 10fs using ultrafast optical spectroscopy. In our experiments we make real-time measurements of optical absorption, photoluminescence and inelastic light (Raman) scattering using ultrashort pulses generated by modelocked lasers. These measurements provide important fundamental information about electron-electron and electron-phonon interactions, and they are of great practical significance since the ultimate speed of electronic and optoelectronic devices is limited by these processes. The signature of interacting quantum systems is predicted to include distinct non-classical optical characteristics. The group has pioneered quantum optical measurements of semiconductor structures, e.g. semiconductor waveguides, and is now extending this work to quantum structures.

Carrier dynamics and stimulated emission from wide-band-gap semiconductors

J F Ryan, R A Taylor

The development of full colour light sources based on semiconductor lasers is an important goal in the fields of optical displays and communications. The physical mechanism giving rise to stimulated emission in wide-band-gap materials required for producing blue lasers is not understood, although it is believed to involve strongly correlated electrons and holes (c.f. excitons). Free carrier and exciton dynamics are currently being investigated in both bulk and quantum well structures in wide-band-gap III-V materials of the GaN family. Experiments use time-resolved photoluminescence, optical absorption and reflectance spectroscopy. Optically-pumped lasers are being studied in order to develop an understanding of excitonic scattering and localisation processes, plasma formation and energy relaxation. The Kerr gating technique is being used to achieve a time resolution of ~500fs in the gain experiments**.**

Flying qubits from quantum dots

R A Taylor

As part of a new Interdisciplinary Research Collaboration in Quantum Information Processing, starting in April 2004, the optical properties of III-V nitride and arsenide quantum dots are to be investigated. The goal of the whole project is the eventual development of quantum coherent interconnects (flying qubits) for systems based on a condensed matter-based implementation of a quantum logic gate. One candidate for such a scheme is based on quantum dots of the wide-bandgap nitride system, and another is based photonic crystals in the well-developed InAs quantum dot system. The dynamics of recombination in a single dot will be investigated using time-correlated photon counting techniques, and coherent control will be used to determine the dephasing times present in the system. The control of the photon mode around the dot will be investigated using Bragg mirror cavities and photonic bandgap structures. The work will be undertaken in collaboration with the Microelectronics Research Laboratory in Cambridge and the Hitachi Cambridge Laboratory.

Photonic crystals

A J Turberfield with R G Denning (Inorganic Chemistry Laboratory)

Photonic crystals (or photonic band gap structures) are microstructured photonic materials in which the dielectric constant is periodically modulated on a length scale comparable to optical wavelengths. Multiple interference between light waves scattered from each unit cell of the structure may open a ‘photonic band gap’ — a forbidden frequency range, analogous to the electronic band gap of a semiconductor, within which no propagating electromagnetic modes exist. We have developed a uniquely .exible photochemical technique for the production of photonic crystals with bandgaps in the visible region of the spectrum [M. Campbell, D.N. Sharp, M.T. Harrison, R.G. Denning and A.J. Turberfield, Fabrication of photonic crystals for the visible spectrum by holographic lithography. Nature 404, 53 (2000)]: this is the basis of our research into the fabrication, optical characterisation and physics of sub-micron microstructured photonic materials. Local structural modification of a photonic crystal may give rise to spatially localised electromagnetic modes at energies within the gap, allowing the construction of wavelength-scale resonators and, by coupling defects together, waveguides. A waveguide operating at a frequency within a photonic band gap cannot leak – there are no propagating electromagnetic modes in the surrounding photonic crystal capable of carrying energy away. Our current focus is on the development of microcavities and waveguides within photonic crystals, motivated by a view of the future of photonic crystal engineering which sees waveguides and cavities operating at frequencies within a photonic band gap as the basis of miniaturized integrated optical circuits and of novel optoelectronic devices from thresholdless lasers to entangled quantum states and quantum computation.J F Ryan

The microscopic origin of electron pairing in high T_c superconductors is still unknown despite considerable effort over the past ten years. The materials of interest, such as YBCO, are semiconducting at low dopant concentration, and undergo a semiconductor-metal transition as the doping level is increased. Femtosecond time-resolved reflection and transmission spectroscopy is being used to study the dynamics of electron relaxation and pair formation in single crystal samples prepared in the Department. Polarization studies reveal information about symmetry of the pairing mechanism by measuring anisotropy of the superconducting gap.

Thin film samples of these materials have important potential optoelectronic applications, principally in the areas of high-speed, broadband photodetectors and the generation of THz radiation using femtosecond pulsed lasers.

3 Magnetism

Spin electronics

J F Gregg

Conventional electronics has ignored the spin of the electron. Indeed, with the exception of solenoids, relays, Hall sensors and the occasional specialist microwave device, magnetism has traditionally been the ‘poor relation’ in the world of electronic circuitry. In the everyday silicon transistor, the different families of electrical carrier are distinguished by their different effective charges: however no practical use is made of the fact that some are spin-up and others are spin-down.

The recognition of this distinction is the key which promises to unlock a whole new generation of spin electronic devices whose operation relies upon differential manipulation of independent families of current carriers with opposite spin polarisation.

The technical basis for spin electronics rests on the fact that electrical currents in ferromagnets are carried by two distinct and independent ‘spin channels’, one consisting of electrons with spin parallel to the magnetisation and the other with spins antiparallel. The relative independence of these two families of carriers arises since, although spin flip processes are possible which move electrons from one channel to the other, they occur on a timescale which is long compared with those of other processes. Moreover, the carrier mobilities of the two channels are very different, and this implies that small ferromagnetic elements incorporated into spin electronic devices may be used to encode magnetic information onto the conduction electrons.

The nature of the coded information may be externally varied by application of magnetic fields which change the magnetisation states of the encoder ferromagnets.

Spin electronic devices work by transferring this spin information from one part of the device to another where it is subsequently ‘read’. The information is mediated by the electrical carriers and it decays on a characteristic length scale (the spin diffusion length) which is the average distance diffused by a carrier spin before flipping. This can vary from nanometers to microns depending on material. An essential criterion for the creation of spin electronics is thus the ability to engineer structures whose physical dimensions are of this order or smaller. With the advent of modern thin film and nanofabrication technology this dream is now a reality.

Potential applications of spin electronics lie in the data-storage industry as might be expected, but also in programmable gate arrays, robotics, and precision engineering where fast accurate position and motion sensing of mechanical components is a requirement. In particular, there is a growing awareness of the need for such technology in the development of improved fuel handling systems and electronic engine control in the automotive industry. The requirement for robust, temperature stable, high signal-to-noise sensors extends to many other aspects of automobiles including antiskid systems, speed controls and crash avoidance.

The Oxford Spin Electronics Group is currently supported by the European Commission and EPSRC. In collaboration with eight European physics laboratories and two major electronics companies, work is in progress on novel 3- and 4-terminal spin electronic devices. Hybrid designs using semiconductor/ferromagnetic metals are being developed with a view to achieving enhanced gain, signal-to-noise and field sensitivity. The research is wide-ranging and includes fabrication of materials and structures, study of the fundamental transport physics of semiconductor/ferromagnetic interfaces, characterisation of novel spin electronic materials, theoretical modelling of interfacial processes and comparison with non-linear optical studies of real interfaces, study of spin tunnelling processes, design of actual device structures and even implementation of such devices in real automotive machinery.

Single crystals of novel magnetic oxides

A T Boothroyd, S J Blundell

A great deal of new physics has emerged in recent years in doped transition metal oxides. An underlying theme linking these systems is the importance of electronic and structural correlations arising from electron-electron or electron-lattice interactions, which frequently result in phase transitions to magnetic or electronically ordered states. Of particular interest are systems that are close to a phase instability since they have a tendency to exhibit unconventional ground states known as quantum ordered phases.

The tremendous progress made in understanding novel correlated electron phenomena owes much to improvements in methods for preparing what are often quite complex materials. One of the key developments has been the floating-zone method of crystal growth. Single crystals are essential for physics research because many of the most interesting materials have highly anisotropic properties. In addition, spectroscopic techniques that probe charge and spin correlations, such as neutron and X-ray scattering and muon spin rotation invariably require large crystals (~cm^3) with exceptional purity in order to achieve a good signal. Single crystals of a wide range of materials are grown by the floating-zone method in an image furnace. The crystals are used for basic research into interacting electron phenomena by members of the Clarendon laboratory and collaborators outside Oxford.

MBE growth and characterisation of magnetic superlattices

R C C Ward

Novel metal epitaxial thin-film structures grown by molecular beam epitaxy are being investigated for the purposes of fundamental magnetic research and device development. The research interests of the Oxford MBE Group concern the relationship between the structural and magnetic properties of thin-film devices, and include the study of the mechanisms of metal epitaxy and MBE growth, layer and interface quality, as well as the magnetic characteristics of the devices grown. Current research projects include the following :-

Epitaxial spin valve structures which are single-crystal analogues of devices used as GMR (giant-magnetoresistive) read-heads for computer hard discs. These are multilayer structures of transition metal alloys involving two ferromagnetic layers (eg. NiFe), one pinned by an adjacent antiferromagnetic layer (eg. FeMn or PtMn) and the other a sensor layer which responds to the ‘stored’ magnetic moment. In collaborative work with the Department of Materials, we are investigating the properties of the AFM layer and the spin structure at the interface with the pinned FM layer, in order to understand the pinning mechanism in detail. This work will be extended to tunnel magnetoresistive (TMR) devices where the two FM layers are separated by an insulating oxide layer rather than the metal spacer layer in conventional spin valves. Patterning of the structures to nanoscale lateral dimensions will also be investigated. Model elemental systems such as Mn/Fe are also being studied. The MBE technique, where growth takes place far from equilibrium, allows a high-temperature phase of antiferromagnetic Mn to be stabilised in superlattices with Fe at room temperature.

The world’s first Laves phase superlattices (DyFe2/YFe2) were grown at Oxford as part of an extensive MBE growth programme on epitaxial compounds of rare earth (R) and transition (M) metals. These types of bulk compounds already form the basis of high-performance permanent magnets (RM5 and R2M17). The growth of epitaxial multilayers of these materials allows the magnetic properties to be “designed” by changing the individual layer thicknesses and the rare earth elements.

Superlattices involving lanthanum (a nonmagnetic rare earth which becomes superconducting at around 5K) and a magnetic rare earth such as gadolinium are being grown for study of the coexistence/competition between magnetism and superconductivity. This is the latest development of the MBE growth at Oxford of high quality, single crystal superlattices, alloys and compounds of rare earth metals, including the world’s first all-light-rare-earth superlattices, which has enabled new insights into the mechanisms and interactions which determine the complex magnetic behaviour of the largest group of magnetic elements in the periodic table.

Uranium multilayers and compounds

R C C Ward

A new UHV magnetron sputtering facility has been developed to produce thin films of uranium and its compounds for the study of magnetic and other physical properties of this actinide element, thereby opening up an entirely new family of magnetic multilayers. This is a strategic, collaborative project in partnership with the European Institute for Transuranium Research (Karlsruhe), RAL, ESRF (Grenoble), Liverpool University and UCL. The new growth facility at the Clarendon is configured with four magnetron sputter sources, individually shuttered and compatible with DC or RF power sources. Substrate heating is provided to promote the growth of epitaxial layers. Measurements will concentrate on the new physics that uranium will shape via the large orbital moment of the 5f electrons and the effects of the hybridisation of these with neighbouring magnetic atoms in multilayers with transition elements such as iron. While the initial aim is the understanding of the novel magnetic behaviour of these multilayers, it is quite possible that these properties could find application in magnetic sensors, recording and in catalysis. The research will be extended to include compounds of uranium such as oxides and hydrides.

Magnetic structures of rare earth superlattices and alloys

R A Cowley

The magnetic structures of the rare earth and Laves phase superlattices are determined by using neutron scattering techniques with facilities in Canada, in Berlin or at the ILL The samples are grown using MBE techniques in Oxford as described above and the structures determined using in-house X-ray scattering facilities. Experiments are performed to study how this coherence depends on the lattice mismatch, on the crystallographic structure of the two blocks and, when both of the materials are magnetic, the competition between different types of magnetic order. Experiments have been conducted to determine the magnetic structures of $DyFe_2/YFe_2$ superlattices. The results have shown that the direction of the magnetic moment depends drastically on the thickness of the individual layers and rotates rapidly when the moments on the different blocks are very similar. Further work is planned on other systems and will lead to the development of new models of the magnetic interactions between the 3d and 4f elements in these superlattices. Experiments are also in progress to determine the effect of hydrogenation on the magnetic properties of thin films and superlattices and to understand the magnetic structures of the dihyrides and trohydrides of the rare earths.

Quantum phase transitions explored by neutron scattering

R Coldea

Quantum spin systems are an ideal playground to explore the self-organization of quantum states of many particles. Examples include Bose-Einstein condensates of magnons, and quantum spin liquids where quasiparticles are spin-density vortices with fractional spin quantum number. We aim to explore experimentally at the microscopic level the phenomenology of such phases by using neutron scattering to image directly the spin states. Moreover, the quantum fluctuations that dominate the physics can be tuned externally in a very clean way by applied magnetic fields and when the field matches the energy of the exchange interactions transitions to novel types of phases can occur. One of the aims of the experiments is to test the proposed universality of the critical fluctuations at such zero-temperature field-driven phase transitions and to observe experimentally how the wavefunctions and quantum numbers of quasi-particles transform across the transition between phases with distinct quantum order. Current projects study the phase transition from magnetic order to quantum paramagnet induced by transverse field in spin-1/2 Ising- and XY-like magnets. Another investigated topic is frustrated quantum magnets, such as triangular-based antiferromagnets, where frustration leads to strongly-enhances zero-point quantum fluctuations and thus opens up the possibility for novel types of collective behaviour. Recent work includes observation of fractional spin quasiparticles (spin-1/2 spinons) in a 2D frustrated antiferromagnet on an anisotropic triangular lattice and current projects explore the excitations and unusual ordered phases (magnetization plateau, spin-density-wave phases) stabilized by magnetic field in other spin-1/2 frustrated systems.

The work consists in neutron scattering measurements of the magnetic order and spin dynamics in single crystals, grown mainly using the optical floating-zone furnace in the Clarendon Laboratory. The neutron experiments are performed at state-of-the-art international facilities at the ISIS Spallation Neutron Source near Oxford, ILL in Grenoble and HMI in Berlin using extreme sample environment (high fields 15 T and low temperatures 50 mK) and data analysis involves careful comparison with theoretical models.

Single molecule magnets

S J Blundell, A Ardavan

It has recently been shown that a molecular species could retain magnetisation in the absence of a magnetic field. These molecules - termed “single molecule magnets” - represent the smallest possible magnetic storage device, retaining information in a single molecule rather than in a magnetic particle or array of particles. Furthermore, it has been proposed that single molecule magnets could be used as the qubits in quantum computers. The technological possibilities are immense. Conventional methods of preparing small magnetic particles suffer from a rather broad range of particle sizes which leads to a broad distribution of intrinsic switching rates, complicating the interpretation. On the other hand, the chemical synthesis of polynuclear cage compounds is an attractive route to prepare identical molecular clusters. We are using millimetre wave techniques, pulsed ESR, and muon-spin rotation to characterise the energy levels and to understand the quantum nature of the magnetism in these molecules.

4 Superconductors

Magnetism and superconductivity

A T Boothroyd

In recent years increasing evidence has been found for a link between the physics of magnetic ordering and certain types of superconductivity. We aim to investigate this link through fundamental studies on simple model compounds exhibiting novel magnetic and superconducting behaviour. Much of the work is motivated by the desire to understand the mechanism of superconductivity in unconventional systems, such as the layered cuprate high-T_c superconductors.

Most of the information is obtained by neutron scattering experiments, performed at neutron sources abroad e.g. France and Germany, and at the Rutherford Appleton Laboratory near Oxford. Neutron scattering is a very powerful technique for studying atomic and magnetic arrangements and their dynamics. Microscopic interactions can be probed directly by measurements of e.g. magnetic structures, spin waves, spin fluctuations, lattice vibrations, etc. Many of these experiments employ crystals grown by the optical floating-zone method in the Clarendon Laboratory. Experiments are also performed in the laboratory with techniques that include magnetisation, susceptibility, resistivity and specific heat. A 7 tesla SQUID magnetometer has recently been installed in the laboratory for highly sensitive magnetic measurements. Emphasis in the work is placed on quantitative analysis of the data using the latest data processing methods, some of which are developed within the group. The results are used to make direct tests of the latest theories.

Current problems of interest include:

i) magnetic structures and spin fluctuations in cuprate high-T_c superconductors and related, low dimensional quantum magnets

ii) orbital fluctuations in rare earth and transition metal systems

iii) charge and spin ordering in doped antiferromagnets

iv) novel methods of data analysis and visualisation.

Neutron Scattering from Cuprate High-T_c Superconductors

B Lake

The mechanism driving high-Tc cuprate superconductivity is not yet understood. Current theories range from quasi-particle models where high-Tc superconductors are similar to conventional superconductors and the pairing occurs between weakly interacting quasiparticles. An alternative view is that the electrons organize into collective textures (e.g. charge and spin ‘stripes’) which cannot be mapped onto the electrons in ordinary metals. A third description of high-T_c superconductivity is based on the hypothesis that the cuprates possess hidden ‘SO(5)’ symmetry where magnetic and superconducting order parameters can be ‘rotated’ into each other.

The phase diagram of a cuprate high-T_c superconductor is highly complex, including antiferromagnetic order, striped magnetism and spin-glass phases in addition to superconductivity, and it is thought that the presence of magnetic fluctuations is vital to the superconducting process. The technique of neutron scattering can be used to investigate the magnetism. Neutrons are sensitive to the magnetic moments of a material but not to the values of the charges, and can thus give a clean measurement of the magnetic system. In addition the technique of inelastic neutron scattering is unique in that it provides the full energy and wavevector dependence of the magnetic excitation spectrum. In the past several years I have been part of an international collaboration to investigate the simplest high-T_c superconductor $La_{2-x}Sr_xCuO_4$ using the technique of both elastic and inelastic neutron scattering. The experiments have taken place at various international laboratories in Europe (HMI, Risø, ILL).

Our most recent data shows that an applied magnetic field greatly enhances the magnetic response of a cuprate superconductor. These results imply that the vorticies created by the field are antiferromagnetic. Furthermore the large correlation length of the magnetic signal shows that the antiferromagnetic regions extend well beyond the vortices and into the surrounding superconducting regions; indeed for $H>=H_{c2}$ it is likely that the underdoped system (x~0.10) becomes an antiferromagnet rather than reverting to it non-magnetic normal state as is the case for conventional superconductors. A simple quasi-particle picture cannot explain our data and in addition the results are surprising because they suggest that superconductivity and magnetism which are thought to exclude each other in conventional SO(5) theories may in fact co-exist.

Future work will include small-angle neutron scattering measurements to see the flux-line lattice and hopefully the extended antiferromagnetic regions that are associated with them. Also further experiments to test ‘stripe’ theories and other models of cuprate high-T_c superconductivity.

New states of matter in organic superconductors

A Ardavan, S J Blundell and A-K Klehe

In recent years, the number of scientific publications concerning crystalline organic molecular metals and superconductors has overtaken that on the high T_c cuprates. The reason for this intense interest in organic molecular metals is that they form a uniquely flexible system for the study of superconductivity, magnetism and the effects of electron correlation. The organic metals share many features with the cuprates — a quasi-two-dimensional bandstructure, the proximity of antiferromagnetism, superconductivity and Mott insulator states, spin-charge separation, p-, d- and (perhaps) f-wave superconductivity — and yet they are much cleaner systems; the exact Fermi surface-topology of the organic metals may be deduced using a variety of accurate techniques, whereas this has proved impossible in the cuprates. Moreover, the relatively low critical fields of the organics mean that laboratory magnetic fields can be used to drive them into a variety of novel states.

Organic superconductors are intrinsically anisotropic because of their layered structure and this has important consequences. First, the anisotropy of their band structure implies that with a magnetic field applied along certain directions, the orbital component of the magnetization can be completely suppressed allowing Cooper pairs to survive to much higher fields. Second, the vortex lattice can become unstable leading to a rich variety of dynamic vortex structures that can be probed by, for example, muon-spin rotation. Third, the intrinsic low-dimensionality permits exotic types of pairings and correlations. In particular, we have discovered strong evidence for a phase transition within the superconducting state at high fields which could signal the onset of the so-called Larkin-Ovchinikov-Fulde-Ferrell state. In other systems we also observe behaviour analogous to superconductivity arising from the interplay between charge-ordered electrons and magnetically quantized electrons, which may provide an entirely novel mechanism for dissipationless conduction.

Correlated electron systems under pressure

A-K Klehe

Correlated electron systems is the collective name of materials in which the strong correlation or interaction between electrons is the dominant factor in determining the materials electronic properties. Organic metals, superconductors, heavy fermion metals and colossal magnetoresitance materials are just some of those materials summarized under this term. Very frequently, however, new discoveries of materials or behaviour coincide with a lack of understanding of the origin of the observed behaviour and systematic investigations are essential.

Pressure is a thermodynamic variable that offers the opportunity to systematically vary the interatomic separations and thus to tune the electronic correlations. Knowing the pressure-temperature phase diagram of a material characterizes the interactions in a material and elucidates on possible interaction similarities between different materials, i.e. the similarity in the pressure-temperature phase diagram of cuprate superconductors and organic molecular metals has spurred suggestions of similar d-wave Cooper-pair coupling mediated by antiferromagnetic fluctuations. The pressure-temperature phase diagram of a material can be considered the characteristic fingerprint of the relevant interactions.

Of special importance for my research are organic molecular metals: they have long been used as test materials for physics of the quasi-1 (1D) and quasi-2 (2D) dimensional Fermi surfaces. Their Fermi surfaces can be easily calculated and their intrinsic purity, tuneability and small critical fields makes them suitable for Fermi surface measurements, i.e. Shubnikov-de

Haas, de Haas -van Alphen or AMRO measurements. There isgrowing evidence, based on the similarity in phase diagram that organic superconductors could be considered "test beds" for other superconducting correlated electron systems such as cuprate superconductors or heavy fermion superconductors.

Organic metals are ~10 times more compressible than normal metals, thus making them ideal candidates for investigating their pressure-temperature phase diagram. Within a relatively small pressure range (< 3 GPa) organic molecular metals can exhibit a multitude of different groundstates.

The pressure techniques applied will be the magnetotransport measurements in cylinder piston and He-gas pressure cells as well as infrared reflectivity measurements in diamond anvil cells and optical He-gas pressure cells.

Applied superconductivity and magnet development

H Jones

(See also the high magnetic field facility under Research Support Facilities, page 79)

The magnet group's use of superconductors and other materials for high field magnets has resulted in applied programmes of research and the group includes students doing DPhils in these areas of high technology which cross the boundaries of engineering, materials science and physics.

Superconductors — high and low temperature

High magnetic fields are a primary requirement of condensed matter physics, particularly in combination with low temperatures. An important subdivision of high field generation is superconductivity. Without the huge power supplies needed for conventional electromagnets, moderately high fields (of order 20 tesla) can be generated using state-of-the-art Low Temperature Superconductors (LTS) in wound coils operating at liquid helium temperatures.

High Temperature Superconductors (HTS), discovered by Nobel Laureates Bednorz and Muller in 1986, open up two prospects. Firstly high current electrical engineering applications at temperatures in excess of liquid nitrogen (77 K) become possible and, at lower temperatures, the very high critical magnetic fields of HTS enable next generation superconducting magnets for, say, 25 tesla and beyond. This group works on all aspects of the characterisation, analysis, modelling and real, direct applications of modern superconducting materials, both high and low temperature. This applied research attracts frequent interest from industry.

The latest projects include trapping record levels of flux in bulk large grained rare–earth /YBCO materials using pulsed magnetic fields and addressing applications such as superconducting motors, levitation transport and magnetohydrodynamic marine propulsion.

High field pulsed magnets

As well as providing and servicing a pulsed field facility the group also does research on conductors and magnets for the very highest fields. This is an area with strong international interest and the group interacts with many like laboratories world-wide in order to exploit the latest materials and designs. This way the fields available (of order 100T) are continually improving provided we can combat the extreme conditions of stress, temperature and voltage encountered in this technology.

5 Structures, excitations and phase transitions, defects and impurities

Crystallography of phase transitions and physical properties of crystals

A M Glazer

The Crystallography Group studies the fundamental link between crystal structure and physical properties, mainly optical. Experiments are carried out using X-ray and neutron diffraction, optical polarimetry and other optical techniques. Phase transitions too are studied, not only for their intrinsic interest, but because they often reveal the connection between crystal structure and physical property. Present interests include a structural investigation of perovskite-based crystals, especially lead zirconate-titanate (PZT), new ferroelectric crystals, and the development of a new type of birefringence microscope which has potential applications in materials science, crystallography and in biology/medicine. The Crystallography Group has an interest in developing new instruments within the field of crystallography with an eye on commercial exploitation. The successful local company Oxford Cryosystems sprang from this group, and is the world's leading supplier of low temperature apparatus to crystallography laboratories.

Superlattices and thin films

R A Cowley

X-ray scattering techniques enable very detailed measurements to be made of the structure of thin films and superlattices. Experiments are in progress to study the detailed structure of thin layers grown on top of substrates with a different lattice parameters. When the layer is thin it accommodates the strain and has the same lattice parameter as the substrate. On increasing the thickness mis-fit dislocations are produced to relieve the strain. We are studying this change in behaviour to determine the critical thickness for the onset of misfit dislocations of both metallic and semiconducting systems and the detailed structures of the thin films both above and below the critical thickness. This information is needed both to improve the technological applications of thin films and also to compare with theories of layer growth. The structure of superlattices is also being determined with x-ray scattering techniques. In particular we are interested in determining whether the interfaces are flat and whether the roughness is coherent between the different interfaces or whether it is incoherent. Another set of experiments is concerned with superlattices such as Ge/Si on Si that form elf-assembled arrays of quantum dots inside almost perfect Si. The measurements will determine the size, shape and strain associated with the dots.

Structural disorder at high temperature and high pressure

D A Keen

The nature of disorder within solids is increasingly becoming an important area of academic research as the physical properties of many new materials are critically dependent on the disorder within their structure. Within long-range periodic crystalline materials local disorder may originate from a number of different processes, such as alloying, chemical doping, thermally activated defects or molecular motion. In the extreme of an amorphous material, long-range periodicity is also lost and order may only be evident within the local chemically bound environment. Scattering experiments (whether neutron or X-ray) play an important part in understanding the nature of structural disorder, particularly when the diffuse scattering is considered. These experiments, in tandem with Rietveld refinement and computer modelling, have been used to determine the characteristic structural disorder associated with a number of diverse systems, including the local response to the high-low phase transitions in quartz and cristobalite, the disorder associated with the ionic mobility in superionic conductors and the relationship between the structures of chemically identical systems which exist in different crystalline and amorphous phases.

High pressure structural physics is currently an extremely active research area. Many disordered systems change significantly as temperature and/or pressure is varied, often resulting in a large variety of distinct structural phases at high pressure and high temperature. X-ray and neutron scattering measurements at high pressure and high temperature are underway to characterise these structures and to understand the influence of reduced density and increased thermal energy on the disordering processes. These measurements are carried out at the ISIS Facility, Rutherford Appleton Laboratory, and at the ESRF in Grenoble, using a combination of in-house pressure cells and those available at the central facilities. This work aims to develop still better methodologies for high pressure data collection, analysis and interpretation, leading to a more robust understanding of structural disorder at high pressure.

6 Correlated electron and ion systems

A Ardavan, S J Blundell, A I Coldea, W Hayes, A-K Klehe

Traditionally, fundamental solid-state physics has almost exclusively involved the study of inorganic elements, alloys, and simple compounds, the underlying assumption being that fundamental physics research is most usefully concentrated on chemically simple materials. However, we believe this assumption is often misplaced, and that in fact some of the most exciting studies in solid-state physics can and should be attempted on organic materials which are chemically very complicated indeed. This is not because there are no more fundamental questions to answer concerning more simple materials; rather, the attraction of many organic molecular systems is that though chemically complex, in other ways they are beautifully simple and can often provide much more information about basic phenomena like superconductivity and magnetism.

Organic charge-transfer salts of molecules such as bis(ethylenedithio)tetrathiafulvalene (ET) are being used as ‘test beds’ for current theoretical ideas. We have demonstrated that the ET salts exhibit features characteristic of electron-electron interactions in narrow bandwidth metallic systems and that they have much in common with high T_c cuprate superconductors and heavy fermion compounds. However, in contrast to the latter two systems, ET salts may be probed using reasonable magnetic fields (10–50 T) and temperatures (0.02–6 K). Sample purity is high due to advances in growth techniques driven by potential opto-electronic applications, so that quantum behaviour is readily observed.

Magnetic quantum oscillatory effects are used to deduce the Fermi surface topology and effective masses in the ET salts. Measurements are carried out in Oxford using superconducting magnets (17-21 T) or in fields of up to 33 T at Florida State University. Techniques have been extended to fields of up to 60 T in the Oxford pulsed field facility, and at the Los Alamos National Laboratory. Experiments are also carried out at pressures of up to 30 kbar. In addition members of the research group are scheduled to take part in the DIRAC series of explosive flux compression experiments, which generate fields of up to 1000 T.

Further details may be found on our web site: http://groups.physics.ox.ac.uk/cmphys/correlated

Millimetre-wave magneto-optical spectroscopy

A Ardavan, S J Blundell, W Hayes, A-K Klehe

The Correlated Electron Systems Group has pioneered the use of millimetre-wave and far-infrared spectroscopy as a direct gauge of the strength of electron-electron and electron-phonon interactions in solids. A mm-wave network analyser (the only one in the UK) is used as both source and detector in the frequency range from 8 to 800 GHz (equivalent to 0.35 K-35 K). Recent achievements of this work include the first measurements of the bulk conductivity of metallic systems at GHz frequencies, the first observation of a completely new type of magnetic resonance, the Fermi-surface traversal resonance, and the first mapping of the anisotropic order parameter of a d-wave superconductor using a contactless technique. Optical measurements on a Bruker spectrometer, from 300 GHz to the visible, are used to characterise the intramolecular, charge-transfer, interband, intraband and vibrational excitations and the corresponding molecular and intermolecular (band) parameters, electron correlations and electron-phonon interactions. These techniques, proven on ET salts and conducting oxides, are being extended to other organic materials such as fullerenes and polymers, and to biological molecules such as proteins and prions.

Muon-spin rotation

S J Blundell, W Hayes

Spin-polarised beams of positive muons are produced at the ISIS pulsed spallation source near Oxford and at the Paul Scherrer Institute near Zürich. Though short-lived, these particles can be implanted into virtually any material and used, through a measurement of the time dependence of their spin polarisation, as a very sensitive microscopic magnetometer. The frequency of the Larmor precession signal from a muon gives a direct measurement of local magnetic or hyperfine fields. Recent experiments include studies of the magnetisation in organic ferromagnets and antiferromagnets, the field distribution in the vortex lattice of organic superconductors, the dynamics of spin excitations in conducting polymers and the molecular dynamics of liquid crystals.

Frustration and order in magnetic oxides

S J Blundell

Colossal negative magnetoresistance has recently been found in certain manganese oxides with a layered perovskite structure. We study these materials using muon measurements, in conjunction with high-field magnetoresistance, a.c. impedance, magnetic susceptibility and neutron spin-echo, in order to understand the origin of the effect, which is believed to be connected with novel correlation and exchange mechanisms. We are also investigating systems in which the dominant magnetic coupling is mediated not only by oxygen but by sulphur or hydrogen.

Frustration occurs when it is not possible to satisfy the microscopic interactions in a system. It can occur because of competing interactions or becomes of geometric properties of the crystal lattice. Such systems do not have a long range magnetically ordered ground state, but a large number of equally unsatisfied metastable ground states. Frustrated systems have unusual low energy dynamics because of the transitions between these states and these can be probed using muon-spin relaxation experiments.

Nanotubes and fullerenes for quantum computing

A. Ardavan

As part of a LINK project with Oxford Materials and Cambridge University we are investigating the use of carbon nanotubes and fullerenes in quantum information processing. Fullerenes can encapsulate other species (either atoms or molecules) to form composite structures (endohdreal fullerenes) with useful properties; one example is endohdral nitrogen in C60 (N@C60), in which the nitrogen retains its atomic character and is well isolated from the external environment. Its isolation is reflected in the long electron spin relaxation times that it exhibits (T1 and T2 are 100 microseconds and 20 microseconds respectively at room temperature and increase at low temperatures), stimulating the recognition of spin-active endohedral fullerenes as "natural" qubits. More than a decade of interest in the chemistry of fullerenes and nanotubes has resulted in a rich literature covering their manipulation, functionalisation and processing. We are applying these techniques to endohedral fullerenes to construct multiqubit structures, such as endohedral fullerene "peapods" and dimers. We characterize these materials using a range of techniques, including transmission electron microscopy, scanning probe microscopy and raman spectroscopy and we examine the magnetic properties using electron spin resonance (ESR). We are working to demonstrate entanglement and simple quantum gates on small systems.

7 Nuclear orientation

N J Stone

Hyperfine interactions and the decay of radioactive isotopes are studied by cooling nuclei to temperatures close to 10 mK. At such temperatures the nuclear spins can be polarised, resulting in a spatial anisotropy of the radioactive decay products which is characteristic of the strength of the ordering interaction and of the decay process. The angular distribution is measured in high resolution semiconductor detectors.

Both solid state and nuclear physics investigations are pursued. Current solid state studies include the measurement of nuclear magnetic interactions in ferromagnetic metals and alloys, the samples being frequently produced by ion implantation methods, the study of enhanced nuclear magnetism in some rare earth compounds, and measurement of the coupling of nuclear electric quadrupole moments with the electric field gradients in non-cubic metals. In this work active use is made of a combined technique of NMR on oriented nuclei which affords both high precision and high sensitivity.

Nuclear physics investigations include the systematic study of nuclear magnetic dipole and electric quadrupole moments by orienting series of isotopes in a lattice of known solid state properties. See section 3.2 under Particle and Nuclear Physics on page 60 for further details.

Data analysis involves extensive computation, and nuclear model calculations are made to give interpretation to the results obtained.

8 Biological physics

One of the important challenges in biological physics is to characterise the behaviour of single molecules: for example, how do proteins move, generate force, respond to applied force, and how do they unfold? Biological molecules and systems also have a number of attributes that make them highly suitable for nanotechnology applications. For example, proteins fold into precisely defined three-dimensional shapes, and nucleic acids assemble according to well-understood rules. Antibodies are highly specific in recognising and binding their ligands, and biological assemblies such as molecular motors can perform transport operations. The assembly, control and manipulation of such systems is an exciting prospect, with important scientific and technological implications.

Molecular motors

R Berry with J Armitage (Microbiology)

Rotary molecular motors: The bacterial flagellar motor is a rotary molecular engine powered by the flow of ions across a bacterial cell membrane. Each motor rotates a protruding helical filament at several 100 Hz, providing the propulsive force for cells to swim. The heart of the motor is the rotor - a set of rings about 45nm in diameter, containing a few hundred molecules of several different proteins, surrounded by a ring of up to 16 independent torque generators which are attached to the cell wall. The enzyme F_0F_1-ATPase consists of two rotary motors connected back-to-back, with a rotor diameter of about 10 nm. The ion-driven F_0 motor pushes the ATP-driven F_1 motor backwards, thereby generating most of the ATP that powers metabolic processes in all living things. The objective of the research is to measure the physical behaviour of these motors and to establish the principles by which they work.

Single-molecule fluorescence: The bacterial flagellar motor is controlled by a network of interacting signalling proteins which processes information about the external environment and passes it to the motor. We are investigating this network by following the movement of proteins within single cells, using Green Fluorescent Proteins (GFPs) as a tag. Protein interactions can also be monitored by resonant energy transfer (FRET) between different GFPs.

Experimental techniques being used include laser interferometry, single molecule fluorescence and differential interference contrast (DIC) microscopy, electro-rotation and optical tweezers. Nanometre displacements and pico-Newton forces can be applied and measured. Motor mechanisms are modelled as transitions between a small number of discrete kinetic states driven around a ‘mechano-chemical cycle’ by ion flux or ATP hydrolysis, leading to torque and rotation.

DNA and protein nanostructures

A J Turberfield

Highly specific molecular recognition between strands of DNA can be used for nanostructure fabrication; two- and three-dimensional structures can be made by self-assembly of synthetic oligonucleotides whose base sequences are designed to control the way in which they hybridize [A.J. Turberfield, DNA as an Engineering Material. Phys. World 16 No. 3, 43 (2003); N.C. Seeman, DNA in a material world. Nature 421 427 (2003)]. DNA may be used as ‘addressable glue’ to form bonds between other elements of a many-component system. Self-assembly of DNA structures may be used to perform massively parallel computation. It is even possible to construct active nanostructures whose motion is powered by DNA hybridization.

Synthetic molecular motors: We have already demonstrated the operation of molecular tweezers made from and driven by DNA [B. Yurke, A. J. Turberfield, A. P. Mills, Jr., F. C. Simmel and J. L . Neumann, A DNA-fuelled molecular machine made of DNA. Nature 406, 605 (2000)]. Forces generated by the hybridization of the DNA fuel are ~10pN, of the same order as those generated by biological molecular motors. Physical techniques used for the study of biological motors, including single-molecule optical and force measurements, will be applied to the study of self-assembled molecular machines with the aim to produce free-running molecular motors with the ability to move along a track – a prototype molecular conveyor belt or production line. [A.J. Tuberfield, J.C. Mitchell, B Yurke, A.P. Mills, Jnr, M.I. Blakey and F.C. Simmel, DNA Fuel for Free-Running Nanomachines. Phys. Rev. Lett 90. 118102 (2003)].

DNA scaffolds for crystallography.: We are developing two- and three-dimensional periodic structures made from DNA with unit cell sizes ~10nm. Proteins may be attached at regularly spaced anchorages on these DNA scaffolds to produce artificial protein crystals. In collaboration with Prof. D.J. Sherratt and Prof. L.N. Johnson of the Department of Biochemistry we are exploring the use of these ordered structures for crystallography: we aim to develop this technique to study the structures of proteins and of multi-component molecular machines that are difficult to crystallize by other means, and to study protein-protein interactions.

Functional biomolecular devices: We are also investigating electrical interfaces to biomolecules, and the use of self-assembled machines to manipulate the components of biological systems in order to study their interactions. The aim is to construct devices, based on biological design principles and molecular recognition.

Biomembranes and ion channels

J F Ryan with A Watts (Biochemistry) & M Sansom (Molecular Biophysics)

A major challenge in structural biology is the resolution of structure and function of membrane proteins, not least because of the large influx of primary sequence data being generated from the various genome projects. One new application in biomembrane research of optical methodology is single particle tracking and optical tweezers, where the chromophore is the ligand. Optical techniques including tweezers and near-field microscopy will help us get new information to complement structural data obtained from solid state NMR, X-ray crystallography and theoretical modelling.

Ion channels are an important class of membrane proteins. Their functional behaviour is based on two fundamental processes: permeation and gating. The crystal structure of one such channel, the Streptomyces K^+ channel, KcsA, has recently been determined at 3.2Å which reveals for the first time details of the selectivity filter and suggests a dynamical mechanism for the channel operation. It will be important to test these ideas using optical probes using natural and inserted chromophores. Single crystal samples are available for “conventional” luminescence and light scattering studies. Individual channels may be investigated by single-molecule optical techniques using tweezers and near-field spectroscopy. Microscopic numerical simulations of ion channel dynamics will be used to interpret and guide the experimental programme.

9 Theory

N F Johnson

Our research focuses on emergent phenomena in complex, dynamical systems involving many interacting particles or agents. The general theme of our research is how complex behaviour, or Complexity as it is known, emerges in a system as the number of interacting objects making up that system increases. In everyday language this can be expressed as, 'two¹s company, three¹s a crowd' or 'more is different'.

Complexity in the quantum regime: quantum information processing

We explore exotic quantum phenomena in nanoscale systems with a view to implementing quantum information processing. These nanoscale systems may be artificial (e.g. semiconductor quantum dots), naturally occurring (e.g. biological proteins) or, thinking more to the future, some hybrid of the two. As the scale of such systems is reduced, and they are probed on ever shorter timescales (e.g. using ultrafast femtosecond optics), quantum effects such as state superposition and entanglement become more important. We seek ways of exploiting these effects rather than merely tolerating them. Apart from the obvious practical importance in terms of next-generation technologies, such research is fundamental from the perspective of physics since it addresses the full complexity of the quantum mechanical world. Such complexity, in terms of multi-partite entanglement and its classification, is arguably the major unsolved mystery of modern physics.

Complexity in the classical regime: biological and socio-economic networks

The real world has many examples of complex systems and networks, including biological and socio-economic systems. Recently there has been a major drive to understand such systems as a set of interacting 'agents'. Although each agent typically has fairly simple behavioural rules, their collective dynamics can lead to novel emergent phenomena. Such systems are difficult to understand and manage because of a lack of general 'laws' governing their behaviour. However we are beginning to make progress on certain specific problems in this area, giving hope that more generic principles may soon arise. Of particular interest would be the identification of new principles regarding organization, design and management in complex systems and networks. As an example, we are working directly with experimentalists in the biological sciences, who are looking at the organization, structure and function of organisms such as fungus and slime-mold -- such systems are remarkable in their ability to self-organize and function in an autonomous way without any central control. Part of their survival strategy may involve changing the links between agents to modify the structure of the network, as well as modifying the behaviour of each node.

Our group is part of a research cluster involving other departments in Oxford, and various overseas institutions (e.g. NASA Ames Research Center, California) that compares and integrates complex system ideas from physics, mathematics, biology, engineering, management studies, manufacturing and computer science.

PARTICLE PHYSICS

Professor Brian Foster

Experimental particle physics is concerned with the study of the fundamental forces and particles of nature by means of experiments carried out both at accelerators and using particles arriving at the Earth from space. The subdepartment of particle physics at Oxford is a large one, consisting of 23 permanent faculty, 4 departmental lecturers, 1 PPARC Advanced Fellow and 23 post-doctoral researchers. The programme of the Subdepartment is consequentially broad, ranging from investigations at the energy frontier with CDF at the Tevatron in the US to the search for the dark matter that makes up most of the universe in CRESST in the Gran Sasso in Italy. We also have a major activity in the construction of complex detectors for the LHC experiments ATLAS and LHCb and for a future linear collider. The Oxford/RHUL Centre for Accelerator Science has just been established by PPARC; it represents a major expansion into accelerator science research with the addition of four new tenured academic posts over the next three years.

Graduate students spend part of their first year on a lecture course in addition to starting their research, and if appropriate spend their second year on-site at their experiment. We have a wide variety of projects available for graduate students, in collaborations of greatly diverse sizes. However, all operate within a supportive Oxford group and work on projects which are integrated into a coherent activity which gives full scope for both individual initiative and achievement as well as ensuring appropriate credit to each individual. Both our laboratories here in Oxford and our experiments at foreign facilities provide access to a high-tech environment and excellent training, whether for research, teaching, industry, or commerce.

We are making major contributions to two accelerator-based experiments that are currently taking data: CDF at the Tevatron at Fermilab near Chicago, which is studying proton-antiproton interactions at the energy frontier; and ZEUS, at the HERA accelerator in Hamburg, which is studying a broad range of physics related to the strong and electroweak interactions and making precision measurements of the structure of the proton. We are heavily involved in the construction of two major detectors to study proton-proton interactions at the LHC starting in 2007, the general purpose detector ATLAS and the LHCb detector, which will study matter-antimatter asymmetry in unprecedented detail. The ATLAS experiment is primarily designed to be sensitive to new physics beyond the Standard Model and to the mechanism of mass generation therein, which may manifest itself as a Higgs boson. Oxford is also hosting the regional "Tier-2" centre for Grid computing, a new computing paradigm necessary to cope with the unprecedented demands on computing power resulting from the enormous data rates at LHC.

A 0.5 to 1 TeV linear e+e– collider is planned to be the next major particle physics facility, overlapping in running time with the LHC. The design of both the accelerator and the detectors is very challenging. Oxford is contributing to a broad range of topics in a coherent UK programme knows as LC-ABD to develop parts of a final-focus system for such a machine. We are working on several techniques to measure the beam sizes and parameters, on precision alignment systems for the accelerator; for the experiment, we are collaborating in the development of a new type of CCD for precise measurements near to the production vertex of the collisions.

We also have a major programme involving various aspects of neutrino physics. The SNO heavy-water experiment in Canada continues to make seminal contributions to the detection of oscillations of neutrinos from the Sun. The MINOS experiment will make more precise measurements of neutrino oscillations with a well-understood neutrino beam travelling 730 km from Fermilab to the Soudan mine, starting in 2005. In the more distant future, a high-intensity 'Neutrino Factory' could allow the measurement of matter-antimatter asymmetry in the neutrino sector. The Oxford group is playing a leading role in the UK's involvement in the MICE demonstration of muon cooling, which is a first step towards a Neutrino Factory.

'Dark Matter', which is believed to be the dominant part of the mass of the Universe, is being searched for by CRESST using detectors running in the milli-Kelvin range. This experiment, and also the laser metrology techniques developed for ATLAS and ZEUS, are examples of the interdisciplinary nature of much of our work, which have led to important collaborations with industry and other areas of science.

The following sections describe each of the experiments. The names listed are those of the academic and post-doctoral staff. Most groups also have engineers and technicians working closely with the physicists on the experiment.

More information on our research and details of how to apply for graduate studies can be found on our web page http://www.physics.ox.ac.uk/pnp/.

1 Search for dark matter particles with CRESST

S Henry, H Kraus, B Majorovits, V Mikhailik

One of the most intriguing open questions in particle and astrophysics is the nature of the missing mass in the Universe. The visible mass of galaxies, such as our own, is an order of magnitude too low to explain the rotational velocities observed in the outer parts of the galaxies. This discrepancy can be explained by assuming that the missing mass is present in some invisible form, called the 'dark matter'. The present structure of the Universe imposes constraints on the composition of dark matter, requiring a good fraction of it to be non-baryonic. Particle physics provides WIMPs (weakly interacting massive particles), which arise from supersymmetric (SUSY) models, as possible dark matter candidates.

Direct searches for WIMP dark matter can be carried out by measuring the recoil energies imparted to nuclei by elastic WIMP scattering. The CRESST experiment (Cryogenic Rare Event Search with Superconducting Thermometers) uses very sensitive cryogenic calorimeters to detect these small nuclear recoil energies of order keV. The experiment is situated in the Gran Sasso Underground Laboratory in Italy to protect the detector from cosmic rays and other backgrounds. Such events would obscure the few interactions per day expected from WIMP scattering in the target, which consists of 10kg of calcium-tungstate. CRESST II is designed to probe WIMP-nucleon cross sections in the 10^{-8} pb region, similar to other experiments; in addition, CRESST's superior detector technology allows verification of the correct scaling of the WIMP-nucleon cross section with mass number by using several different target materials within the same experiment.

CRESST has completed its first phase of running with a sapphire target to explore especially the spin-dependent interaction of low-mass WIMPs. During 2004 the upgrade to CRESST II will be completed, with improved shielding and new detectors capable of distinguishing between nuclear and electron recoil. This will improve the overall sensitivity of the experiment and extend the mass range covered to medium and high WIMP masses. Oxford's major responsibility in the upgrade is the 66-channel SQUID readout system, the wiring system in the ultra-low temperature cryostat and front-end electronics. Further activities include Monte Carlo simulation to understand and then reduce the backgrounds, research into inorganic scintillators as additional target materials, to be used once a WIMP signal is suspected, and data analysis. The project is very interdisciplinary, using low temperature physics (cryogenic detector development) applied to particle physics (WIMPs) and astrophysics (dark matter).

Installation of SQUID sensors for the CRESST dark matter search

2 Solar neutrino oscillations at the Sudbury Neutrino Observatory

S Biller, M G Bowler, N A Jelley, S Peeters

The energy of the Sun and most stars derives from the fusion of protons to form helium nuclei. Some of the steps in this and parallel processes take place through the weak interaction with the emission of neutrinos of the electron type, ν_e. Experiments have measured the ν_e flux to be about one half of the expected rate. If the experiments are correct, then either our understanding of the Sun is seriously wrong, which would be surprising, or 'neutrino oscillations' which imply a non-zero neutrino mass, are reducing the terrestrial flux of electron-type neutrinos, ν_e , in favour of muon and tau neutrinos (ν_μ and ν_τ), for which these experiments either have no or low sensitivity.

In June, 2002, the SNO collaboration, of which Oxford is a part, announced results which demonstrated for the first time that neutrino oscillations are, in fact, taking place! SNO uses a 1000 tonne heavy-water D2O Cherenkov counter capable of detecting both ν_e via the charged-current (CC) interaction ν_e+d = e^-+2p, and detecting all three types of neutrino via the neutral-current interaction (NC) ν+d = ν+n+p. It is the ability to detect ν_μ and ν_τ equally as well as ν_e that allowed SNO to say that oscillations occur. These results from the first phase of SNO were followed in September 2003 by results from Phase II , which was carried out with the addition of two tonnes of sodium chloride (salt) to the heavy water. The addition of salt increased the detection efficiency compared to the pure D2O phase by a factor of approximately three (see Figure 1) and enabled the mixing of the neutrinos to be well determined (see Figure 2).

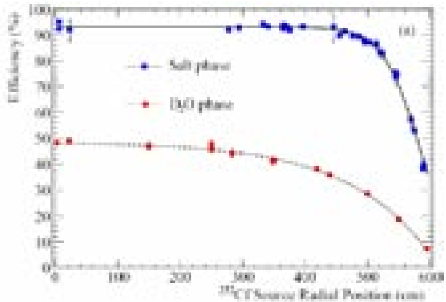


Figure 1 Neutron capture efficiency

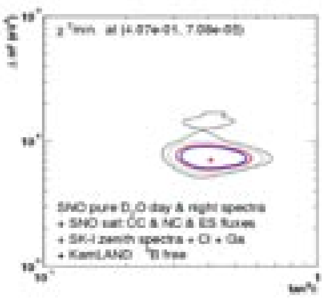


Figure 2 Allowed regions of Δm^2 and $\tan^2\theta$

The final phase started in December 2003 when the installation of 3He neutron proportional counters (NCDs) began. Collecting data with these counters (Phase III) will allow event-by-event separation of CC from NC events, as the neutrons will be detected through the reaction: $n + {}^3He \rightarrow p + t$ .The systematic errors on the NC flux determination are quite different from those in Phase I and Phase II, where neutrons were detected through their associated Cherenkov light, and the results are expected to provide further valuable information on the neutrino mixing parameters and on the total active solar neutrino flux. Phase III is planned to continue until the end of 2006.

The current work of the Oxford Group has two main thrusts:

i) The refinement of methods for analysing the data using the computer simulation and analysis programme SNOMAN developed by Oxford. Oxford carries the central responsibility for computer simulation and analysis. This work not only involves the analysis of neutrino events but also the analysis of backgrounds crucial to the interpretation of the data.

ii) The assay of the radioactivity from the thorium and uranium chains in the 1000 tonnes of heavy water, at a level of one decay per tonne per day, using ultra-filtration membranes coated with hydrous titanium oxide.

3 The MINOS long-baseline neutrino-oscillation experiment

G D Barr, J H Cobb, K Grzelak, N Tagg, A Weber

There is now very strong evidence, from the zenith-angle distribution of atmospheric neutrinos in Super-Kamiokande, Soudan-2 and other experiments, that neutrinos oscillate. Additionally, both SNO and Super-Kamiokande provide compelling measurements showing that the deficit of solar neutrinos detected on earth is a result of neutrino oscillations. Neutrinos must have both mass and 'mix' (as in the K^0-system) for neutrino oscillations to occur. The Standard Model assumes, however, that neutrinos are massless, which means that there is no mixing between different neutrino flavours. A direct confirmation that neutrinos oscillate, thus confirming new physics beyond the Standard Model, can only be obtained with an accelerator experiment.

The MINOS collaboration is constructing a long-baseline neutrino-oscillation experiment. A beam of muon neutrinos produced at Fermilab will be directed to detectors in the Soudan mine, 735 km away. The combination of this baseline and the mean energy of the neutrinos are well matched to the neutrino-oscillation parameters suggested by the atmospheric neutrino results. The neutrinos will be detected by the newly completed 5500 ton MINOS detector. The detector is a toroidally magnetised iron calorimeter interleaved with 92,000 scintillator elements read out by multi-pixel photo detectors.

A smaller detector of similar construction is currently being installed at Fermilab to measure the neutrino flux at source. The first neutrino data set will be obtained during 2005.

The Oxford Group has been active in MINOS since the experiment was first proposed and played a large role in the simulations of the physics capabilities and design of the experiment. The group has taken responsibility for part of the production of the far detector front-end electronics, the clock-distribution systems, the GPS timing system and the near detector photo-detectors and plays an active role in the ongoing test-beam program. The group will continue to develop the offline reconstruction software system based on modern Object Oriented programming techniques and has now started to prepare the analysis of neutrino oscillations with neutral current events.

4 Proton-antiproton collisions at 1.8 TeV with CDF

F Azfar, L Cerrito, B T Huffman, L Lyons, J H Rademacker, P B Renton

The Collider Detector at Fermilab (CDF) is a 3-story-tall detector located at one of the collision points in the Tevatron, a 4-mile-circumference accelerator just outside Chicago in the United States. Here protons and anti-protons are collided head-on at the highest energy yet achieved in an accelerator, close to 2 TeV. The CDF detector is a general-purpose detector capable of collecting data on a wide range of exciting topics in high-energy physics. CDF was the experiment that first reported the discovery of the top quark in 1994, and the Tevatron is still the only facility in the world where these super-massive elementary particles can be produced. CDF has been taking data since April 2001 with an upgraded central tracking system that includes a full 3-dimensional silicon vertex tracker capable of triggering on particles with a large impact parameter. This will enable CDF to trigger on the decays of the B meson.

Some of these B mesons, such as the B_S and B_C mesons, are only produced at the Tevatron. B mesons exhibit mixing, where a particle spontaneously turns into its antiparticle as it travels through space, and CP violation. The first evidence of CP violation between the neutral B meson and its anti-particle partner has already been seen at CDF. This process, which may explain why our Universe prefers matter over antimatter, needs intensive study in the current run of CDF. In addition, within the Standard Model, the Higgs boson is predicted to exist and have a mass small enough to be produced at the Tevatron. Even if the Higgs boson evades scrutiny, analysis of electroweak physics at CDF should place stringent limits on the mass and nature of the Higgs mechanism. One way in which this is done is by precision simultaneous measurements of the mass of the W boson and top quark in one experiment. The Tevatron is the only place where the top quark can be produced, and its decays, mass, and cross section studied. If the top quark were to exhibit anomalous decays, this could point the way to new physics beyond the Standard Model.

The Oxford group is responsible for the operation of the Level 3 trigger, a software trigger written in C++ with the function of removing approximately 4 out of every 5 background events that passed the Level 1 and Level 2 triggers. Several sophisticated methods of triggering on the hadronic decays of the B meson are required in order to reduce the trigger rate and keep as much interesting physics as possible.

5 Electron-proton scattering with ZEUS at HERA

A M Cooper-Sarkar, R C E Devenish, B Foster, G Grzelak, C Gwenlan, B Straub, R Walczak

ZEUS is a large international collaboration studying electron- and positron-proton interactions at very high energies. HERA is a unique facility in Hamburg, Germany, providing e-p collisions at a centre-of-mass energy of 318 GeV from the collision of 920 GeV protons with electrons or positrons of 27.5 GeV. Broadly the areas of study are: strong interactions (QCD); electroweak properties of the proton; physics beyond the Standard Model; the nature of the photon. The Oxford group concentrates on the first three.

The ZEUS central tracking detector was constructed in Oxford and the optical alignment system for the silicon microvertex detector (MVD, installed in 2001) was designed and built by Oxford physicists and support staff. The HERA collider has been upgraded to provide higher luminosity and longitudinally polarized $e^{\pm}$ beams and will run until 2007. The improved charged-particle tracking gives better reconstruction of charm and other short-lived particles.

QCD physics dominated the first phase of HERA operations, particularly exploration of the gluon dominated 'low-χ' regime in which we were heavily involved. At present, we are leading the extraction of parton distribution functions from the very high-precision ZEUS data on the proton structure function. These functions are an essential input to all physics calculations at the Tevatron and LHC. The latest advance is to include high transverse-energy ('E_τ') jet data in the fit.

Our immediate goals are to complete the tuning of the combined tracking system and use it for physics studies of strange, charm and beauty quarks. As data are accumulated with HERA-II over the next few years, our activities will focus more on high-momentum-transfer ('Q^2'), high-E_τ processes and heavy-quark production. These topics involve measuring both neutral and charged current cross sections and processes with large E_τ, particularly events containing high-energy leptons. The use of polarised beams gives additional sensitivity to processes involving weak couplings, such as the extraction of the parity-violating structure function χF_3. In addition, the improved particle identification of our enhanced tracking system will allow much more detailed studies of the final states. This, coupled with lepton identification, will be vital for probing signatures for physics beyond the Standard Model.

6 Multi-TeV proton-proton collisions with ATLAS

A Abdesselam, P Bruckman De Renstrom, R Cashmore, S Cooper, A M Cooper-Sarkar, P Coe, S Gibson,, R B Nickerson, A Reichold, P Renton, J Tseng, L. Vacavant, G Viehhauser, A R Weidberg

The Large Hadron Collider (LHC) at CERN due to start running in 2007 will open up the energy regime an order of magnitude above that currently available. The Oxford group has been active in the early stages of detector design and development and is now involved in the design and construction of one of the large general purpose experiments, ATLAS. The primary goal of the experiment is physics beyond the Standard Model. The energy of the collider is designed to ensure discovery of the Higgs bosons, if it, or they, exist. The LHC will also allow a search for supersymmetric (SUSY) particles, which should be detectable up to masses over 1 TeV. In addition to physics beyond the Standard Model, B production will be copious, affording the opportunity to investigate CP-violation in the B system. Further, large numbers of the t quark will be produced, allowing systematic studies of its properties.

The Oxford group is currently working on the construction of the silicon tracker. The main areas of work are in the areas of support mechanics, assembly and test of the barrel part of the tracker, the alignment and survey systems and the optical read-out. The optical systems required for alignment and survey include novel techniques based on tunable lasers.

The excellent local computing facilities are used to develop the C++ code for the inner-detector pattern recognition and alignment. Work on the computing Grid is underway in order to meet the challenge of the very large data sets that will be generated by ATLAS. The group also works on computer simulation studies of the physics reach of the detector, mainly in the area of SUSY.

7 CP-violation studies with LHCb

M Adinolfi, N Harnew, J H Rademacker, G Wilkinson

CP-violation was observed experimentally nearly 40 years ago in K^0 decays, yet it still remains one of the least understood phenomena in particle physics. It is believed to be an essential ingredient of the mechanism which led to the matter-antimatter asymmetry in our Universe. A far greater sensitivity to the CP-violation mechanism is expected in the beauty-quark system. The LHCb experiment aims to exploit this and is optimized for a dedicated experimental programme of B-physics. The 14 TeV proton-proton centre of mass energy of the CERN Large Hadron Collider (LHC) will provide approximately 10^{12} b-b(bar) pairs per year of running. LHCb does not resemble a 'typical' collider experiment; rather it consists of a forward spectrometer with angular coverage between 10 and 300 milliradians.

The primary task of LHCb is to perform precise measurements of the unitarity of the CKM-matrix and check whether or not it provides a consistent picture of the CP-violation mechanism described in the Standard Model. If it does not, then we will get an insight into new physics that lies well beyond our current understanding.

The LHCb physics programme is based on the measurement of CP violating effects in samples of rare B meson decays. The major interest of the Oxford group is in particle identification which is vital in ensuring the purity of the B meson samples. LHCb posseses two Ring-Imaging Cherenkov (RICH) detectors for particle ID, in which radiated Cherenkov cones are imaged as rings in planes of Hybrid Photon Detectors (HPDs). A high event rate (40 MHz) necessitates complex and state-of–the-art readout electronics. In addition, the large track multiplicity and a variety of background processes means that an LHC event as seen in the photodetector planes is highly complex.

The design and prototyping stage of LHCb will soon be completed and construction of the detector and its readout system will begin. Oxford responsibilities include the design, fabrication and operation of the on-detector electronics readout of the RICH detectors and optical links. In addition, the Oxford group is responsible for the sophisticated pattern recognition and reconstruction techniques that are required to isolate the Cherenkov rings from the decay tracks of interest, and to determine the particle identities. Finally, the group is heavily involved in preparation for physics analysis, including simulation, detector optimization, and computing for the experiment using GRID technology.

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8 Grid Computing

V Bartsch, C Cioffi, F Harris, P Gronbech, I McArthur, R Newman, A Soroko, S Stonjek, J Tseng

Grid computing represents a potential revolution in the way we use computing power and data storage in research: instead of a mere computer on every desktop, we could see the power of supercomputers at the touch of your mobile phone's keypad, with organisational capabilities that could help make sense of a global library of scientific data and results. Indeed, the development and use of the Grid is crucial to the exploitation of the next generation of particle physics experiments, where the computing and storage requirements are at least an order of magnitude greater than before. Much of the particle physics software needs to be modified to take advantage of the Grid and to run efficiently in this complex environment. User interfaces must also be developed to enhance scientists' ability to work more effectively by utilising the Grid.

Current projects within the group include interfacing LHCb and ATLAS code to the Grid, and deploying and extending the "SAM" distributed data-handling system for CDF. The group is also involved in the LHC Computing Grid project in the areas of object-oriented data persistency and cataloguing, and has a leading role in developing a distributed "Tier-2" data analysis centre for LHC experiments as part of a Europe-wide test-bed. Collaborators include the experimental groups from Rutherford Laboratory, Bristol, Birmingham, Cambridge, and Warwick, and the e-Science centres at each of these sites. The group is working increasingly closely with the Oxford e-Science Centre as the development phase moves towards a production service. Group members have also taken leadership roles in European Grid projects, and the group as a whole benefits from close association with CERN-based developments. Collaborations with industry have grown to develop and exploit this technology further, both within and beyond particle physics research. Graduate students in the group will generally be expected to participate fully in the physics program of an experimental collaboration which utilises Grid computing.

9 Future linear e+e- collider detectors

B. Foster, S Hillert, D Jackson

A 0.5 to 1TeV linear e^+e^- collider is expected to be the next major particle physics accelerator, overlapping in running time with the LHC. The collider would be a 'factory' for studying Higgs bosons and possible new particles predicted by supersymmetry, as well as enormous samples of top quarks and vector bosons.

Oxford is a founder member of the UK Linear Collider Flavour Identification (LCFI) collaboration, which is pursuing an R&D programme to develop thinner, larger-area, faster-readout CCDs for use in a vertex detector. The vertex detector will be vital for identifying the decays of new heavy particles, such as the Higgs boson, into bottom and charm quarks. In collaboration with the UK CCD manufacturer, Marconi, we are investigating the production, handling and support of long, very thin (60 microns) CCD ladders, all of which are extremely mechanically challenging. The CCD's should have column-parallel readout at 50 MHz and an intensive programme of testing is being carried out to explore various possibilities for achieving this. We are leading the design and construction of the "off-detector" readout electronics, involving sophisticated clock and control and DAQ. We also have a major programme in the simulation of the detector and its use in the study of a wide variety of physics processes which may be studied at a linear collider, such a Supersymmetry and Higgs-boson production.

10 Accelerator Research and Development

W.W.M. Allison, G.D. Barr, U. Bravar, J.H. Cobb, S. Cooper, G. Doucas, B. Foster, G. Grezlak, A. Mitra, A. Reichold, R. Walczak

The estalishment of the Oxford-RHUL Institute for Accelerator Science by PPARC in April 2004 will be of major importance for our future programme. We intend to appoint a Director in the near future, followed by several additional academic and postdoctoral staff. These will join our already extensive activities in accelerator R&D, which currently centre on two main areas: neutrino factory R&D; and developments for future linear colliders.

Future linear collider research

High-accuracy survey systems beyond current technological limits will play a key role in the installation, operation and maintenance of any future linear collider. These projects involve advance fibre-optical techniques such as high-accuracy interferometric phase and wavelength measurements, as well as extremely complex geometrical calibration and reconstruction procedures. The LiCAS group (Linear Collider Alignment and Survey), in close collaboration with DESY, is actively developing a Rapid Tunnel Reference Surveyor (RTRS) for the next linear collider. The RTRS measurement systems are based on Frequency Scanning Interferometry (FSI) and Laser Straightness Monitors (LSM). These were originally developed at Oxford for the ATLAS and ZEUS experiments. Dramatic improvements to FSI are made possible by the use of very high-performance tunable lasers and Erbium-doped fibre amplifiers operating in the telecommunication wavelength range (1.5 to 1.6 μm).

The necessity to focus the electron positron beams to sub-micron sizes puts unprecedented demands on the beam diagnostics of a future linear colllider. We are involved in two techniques to measure the beam parameters. In one, known as the "laser-wire", a laser is shone onto the beam and detects the back-scattered Compton photons in a calorimeter outside the beam pipe. We are involved in beam tests of this technique at the PETRA accelerator in DESY Hamburg and are planning tests at the ATF at KEK in Japan. A sophisticated laser laboratory dedicated to these studies is being set up in Oxford. The other technique being evaluated, both theoretically and in beam tests, utilises Smith-Purcell radiation from the beams to measure their size.

Neutrino factory research

The observation of CP violation by neutrinos may resolve the long-standing question of why we live in a Universe composed predominantly of matter. 'Neutrino Factories' have been devised to allow more accurate ways of studying neutrinos. In a Neutrino Factory, the muons which are produced when a high-intensity proton beam hits a target are captured, accelerated and stored in a ring. Their subsequent decay would produce intense beams of electron- and muon-neutrinos and allow very long-baseline (10,000km) neutrino-oscillation experiments and the search for CP violation to be performed. There are, however, formidable technical challenges to be overcome before such a facility becomes a reality.

The development of ‘ionisation cooling’, by which bunches of muons are compressed sufficiently to fit into the acceptance of an accelerator, is an important step in the development of a neutrino factory. To cool a muon beam, the muons must be confined by solenoidal magnetic fields and passed through a repeated sequence of liquid hydrogen absorbers and accelerating RF cavities. The proposed ‘MICE’ experiment at RAL is designed to demonstrate that all these components can operate together and that a beam of muons can, indeed, be cooled. The group is involved in designing the superconducting magnets for MICE, integration of the absorbers with the magnets, and optimisation of the beam dynamics and emittance measurements. A detailed theoretical treatment of ionisation energy loss and multiple scattering – the key processes affecting ionisation cooling – has been developed and will be studied. The group will become involved in other aspects of neutrino-factory development, especially novel muon-acceleration mechanisms, as the project progresses.

THEORETICAL PHYSICS

Professor David Sherrington

The sub-department is housed in premises at 1–4 Keble Road. There are 14 permanent members of staff as well as 4 senior research fellows,1 finite-term lecturer and six active Emeritus staff. The research interests spread across most of the areas of physics studied in the experimental sub-departments. There are four loosely coordinated groups working in astrophysics, condensed matter, elementary particle physics and nuclear structure. The techniques of theoretical physics often have wide applicability and there is therefore considerable interaction between individuals in different groups. In particular, the sub-department provides graduate courses from which all graduate students must choose a selection to follow in their first two terms (unless they are excused because of their experience of similar courses elsewhere). This ensures that all students obtain a broad grounding in the techniques of theoretical physics, including those which may not seem immediately applicable to their own research problem but which are often found very useful later. In addition there is a wide variety of seminars of both specialised and general interest, from which members can keep abreast of developments in their own and related fields. The sub-department has a discussion room, well supplied with both coffee and blackboards.

There is a powerful network of UNIX work-stations providing excellent computing facilities, together with access to large external multi-user computers at university and national centres.

The active research programme attracts research grants in all fields, mainly from the research councils PPARC and EPSRC. Additional grants have been obtained from the EC and other bodies while various collaborative projects are underway. These grants, together with ad hominem Fellowships, normally fund about 20 to 30 other postdoctoral researchers within the sub-department. There are also usually about 40 research students, approximately half of whom come from outside the United Kingdom. This high level of research activity attracts many visitors from other research and academic institutions and during a typical academic year some 40 colleagues will have spent varying times in the sub-department collaborating with the various groups.

1 Theoretical astrophysics

1.1 Galaxies and cosmology

J J Binney, J. Magorrian

Much of the work on galaxies, which currently involves two postdoctoral workers and four students, is aimed at the construction of detailed galactic dynamical models. Such models are not only of interest in themselves but are essential for mapping the distribution of matter in and around galaxies. Our work concentrates on two key problems: understanding the global structure of our own Galaxy and understanding the dynamics of the central regions of nearby external galaxies. For example, models developed at Oxford have been used to demonstrate that the disc of our own Galaxy is barred and have constrained the bar’s structure and pattern speed. Models applied to external galaxies have uncovered evidence that most galactic bulges harbour a central supermassive black hole. The implications of such discoveries are investigated using both analytical work and N-body simulation.

Galaxies being systems with long memories, there is a close connection between galactic structure and formation, so work in cosmology and galaxy formation is pursued in parallel with dynamical studies. Work in general non-linear systems is another outgrowth of the sub-department's galactic modeling work. For further details, see section 1.2 in Astrophysics.

1.2 Stellar chromospheres and coronae

C Jordan

The work on stellar chromospheres and coronae, which typically involves two postdoctoral workers and two students, seeks to understand the hot outer atmospheres of cool stars, which are far from thermal equilibrium. The goals are to understand the development of these regions and of stellar winds in the context of stellar evolution, and the cause of the high temperatures. Ultraviolet and X-ray spectra from satellites (e.g. the Hubble Space Telescope, Chandra and XMM-Newton) are used to infer the temperature, pressure and velocity fields as a function of distance above the photosphere. This can involve the use of sophisticated radiative transfer codes. The results are used to determine the cooling by thermal conduction and radiation processes, and hence the energy input required from the release of energy in the reconnection of magnetic fields, or the dissipation of magnetohydrodynamic waves.

2 Nuclear structure theory

B Buck

The group studies a variety of problems in the theory of nuclear structure and reactions.

2.1 Collective motion, clustering

The nuclear group has always been interested in the theory of collective motion and clustering in nuclei and there are several projects in this area. Most of the reaction and structure theory is related to experimental programmes at major labs in Europe and the USA.

2.2 Decay theory

There is a continuing programme of research on the calculation of absolute lifetimes for particle emission from nuclei, especially for exotic decay.

2.3 Inverse problems

A recent interest is the use of probabilistic inference and maximum entropy analysis for the recovery of information on nuclei (and other systems) from sparse and noisy data.

3 Elementary particle theory

In addition to seven permanent and two finite-term academic staff there are eight postdoctoral fellows, three emeritus academics, twenty graduate research students and several visitors making the group one of the largest in the country. This and the presence of several neighbouring research groups working on related subjects provides an excellent environment for research on practically any aspect of particle physics.

3.1 Lattice field theory

M J Teper, J F Wheater

Many non-perturbative problems in field theories can only be addressed by computer simulation. This involves replacing continuum space-time by a discrete lattice of space-time points. Our interests involve many of the outstanding problems in Quantum Chromodynamics (QCD). For example: the masses of glueballs, their fate in the experimental mass spectrum, understanding chiral symmetry breaking, the topological structure of the vacuum and the dynamics of confinement. We also participate in the QCD calculations of the UKQCD Collaboration. Other current interests of ours involve the large-N behaviour of SU(N) field theories.
Using lattice techniques the properties of fluctuating random surfaces and of simplicial quantum gravity are studied from a number of points of view. The main aim is to elucidate the geometrical structure of the typical universes in the quantum ensemble. This is done using mainly analytical techniques (for example, the methods of rigorous statistical mechanics, series expansions, matrix model calculations) although these can be supplemented by numerical work where necessary.

3.2 Phenomenology of electroweak and strong interactions

F E Close, R H Dalitz, J March Russell, G G Ross, S Sarkar

There is an on-going programme of research in phenomenology with the dual aims of testing the Standard Model and identifying new phenomena. A long-standing interest is the nature of hadron dynamics in QCD and the description of glueballs, hybrids and other hadronic states together with their experimental signatures. Analysis of the new precision data on heavy quark systems coming from b quark factories is proceeding together with its implications for quark and lepton masses, mixing and CP-violation. Complementary to this, studies are also proceeding of the phenomenology of neutrino oscillations and its implications for neutrino mass, mixing and CP-violation.

3.3 Quantum field theory

I J R Aitchison, F E Close, M Schvellinger, M J Teper.

There is considerable interest in the variational approach to wave functionals in nonabelian gauge theories with and without quarks, the flux tube model of hadronic states, the 1/N expansion and QCD at finite temperatures with reference to the confinement-deconfinement phase transition.

A substantial programme concerns aspects of quantum field theory at finite temperature. Current areas of interest include: the phase transitions associated with chiral symmetry breaking and with confinement in QED in two space dimensions; effective Lagrangians for non-static phenomena in superconductors and superfluids; chiral anomalies; and induced quantum numbers.

Other field theory studies include: supersymmetric QCD and duality; quantum spin systems; high energy scattering in QCD.

3.4 M-theory and string theory

A Faraggi, J. March-Russell, G G Ross, M Schvellinger, J F Wheater

There is a substantial programme of research in the more formal aspects of string theory. Various mechanisms for the compactification of the ten dimensions of superstring theory down to the four space-time dimensions observed in nature are being considered; this subject is also of interest to Professor Candelas' group in the Mathematical Institute and is important in determining how the Standard Model may emerge as a low energy approximation. The non-perturbative study of M(atrix) theories aims to determine whether they really do afford a description of M-theory and strings. D-branes are studied both from the point of view of their possible relevance as low energy world-volumes (an alternative to compactification) and in their role as the solitons of string theory.

3.5 Conformal field theory and quantum gravity

A Faraggi, M Schvellinger, J F Wheater

Conformal symmetries and their extensions are a powerful tool in the study of field theories. Logarithmic conformal field theories have been a major activity for many years; at present we are working on the properties of these theories in the presence of boundaries. This is of relevance to systems as diverse as a recoiling D-brane and densely packed polymers. Quantum gravity is studied in two dimensions where it has many equivalent descriptions including as a conformal field theory, and in higher dimensions where conformal structures are used in understanding the foundations of the subject. There is also activity in investigating the AdS/CFT correspondence which relates gravity and string theory on a manifold with boundary to conformal field theories on the boundary.

3.6 Physics beyond the Standard Model

A Faraggi, J. March-Russell, G G Ross, S Sarkar

A major component of the research activity is directed towards the study of extensions of the Standard Model of the strong, weak and electromagnetic interactions. The possibilities being explored include superstring theories, Grand Unification, supersymmetry and compactified theories involving large new dimensions. The phenomenological implications of these theories are under study, including the unification of gauge couplings, the quark, charged lepton and neutrino masses and mixing angles, CP-violation, supersymmetric particle production and the production of the Kaluza Klein tower of states associated with new space dimensions. The implications of these ideas for modifications of gravity at large and small scales are also being studied.

3.7 Particle Astrophysics and Cosmology

A Faraggi, J. March-Russell, G G Ross, S Sarkar

The implications for cosmology and astrophysics of both theoretical and experimental developments beyond the Standard Model are being studied. For example, the observationally-founded Big Bang cosmological model is used to constrain theories of massive neutrinos, supersymmetric particles and Kaluza Klein states which may constitute dark matter. There is on-going work on cosmological phase transitions considering the formation of topological defects, and mechanisms for the origin of the baryon number excess of the Universe. The implications for the generation of large-scale structure in the Universe following from an inflationary stage in its evolution are also being studied, both in the context of field theory and string/M-theory. Other interests include the study of the cosmological implications of new large/warped space dimensions, possible astrophysical tests of quantum gravity, and ultrahigh energy cosmic rays as a probe of new physics.

3.8 Two-dimensional field theory

J Cardy

Conformal field theory in 2d has important applications in string theory and condensed matter physics, as well as being mathematically interesting in its own right. Part of what I do involves understanding general CFTs with a view to classifying them and their properties. Recently I have been working on alternative description of CFTs through random conformal mappings (SLE). This has fascinating links with integrable models of the Calogero-Sutherland type. I also work on massive integrable 2d field theories, and in particular on deriving their form factors (measurable in condensed matter applications) from knowledge of their exact S-matrices.

4 Condensed matter theory

The group consists of six permanent staff, a number of senior visitors, typically about ten postdoctoral assistants, and about twenty doctoral students. It is one of the largest condensed matter theory groups in the country, and its breadth of interests reflects both its size and the diverse nature of the subject. Research is presently supported by a large programme grant from EPSRC together with further grants from other sources.

The group benefits greatly from interaction with local experimental condensed matter groups, especially in the Clarendon Laboratory, which provides stimulation and motivation for some of the work. The group's close contact with the other theoretical groups continues to be an important source of cross-fertilization through shared concepts and techniques. It is not unusual for local theoreticians whose principal interests lie in other areas to play a significant role in the condensed matter activities from time to time. There are also valuable interactions with research groups in other departments in the physical and biological sciences and joint projects with several external research laboratories.

The research encompasses a very wide range of systems, behaviours and concepts, and ranges from phenomenological theories for experimental interpretations to fundamental theories of strongly interacting, random or amorphous and critical systems. A wide variety of techniques is employed, which range from intuitive and phenomenological approaches, through computational ones to highly sophisticated field theoretic, renormalisation and topological methods.

Among strongly interacting situations studied, phase transitions and critical phenomena have been prominent, particularly in magnetic systems, superconductors, wetting, cellular automata, and in random systems, including neural networks, with significant and growing interest in non-equilibrium systems. The emphasis changes as the work progresses, but at the time of writing the following specialised topics are among those under investigation.

4.1 Exactly-solvable models in equilibrium and non-equilibrium statistical mechanics

D B Abraham

Recent work has focused on finite-size and surface effects for correlation functions in uniaxial magnets and their analogues. Exact solutions, obtained in Oxford, are interpreted in terms of a coarse-grained bubble model, conformal field theory and functional integrals. Other topics include the stochastic dynamics of random lines and surfaces and the theory of wetting and spreading, exactly-solvable models of surface morphology and phase transitions in surfaces of 3-d crystals, and ab initio investigation of interface Hamiltonians.

4.2 Critical phenomena and field theory

J Cardy

The use of field theoretic methods to study problems in critical phenomena has a long history, dating back to the 1970's. Field theory provides a natural framework incorporating ideas of scaling and the renormalisation group which explain much of the phenomenology or critical phenomena, as well as providing an approximate calculational scheme. In the 1980's this was supplemented by the powerful methods of conformal field theory which give exact information on many classical systems in two dimensions (and one-dimensional quantum systems). In recent years I have been involved in the development of this theory as applied to quenched random systems (for example, random magnets and disordered electronic systems) as well as to 'geometric' critical behaviour such as percolations and self-avoiding walks, which model polymers. New methods are always being developed for these problems, and the most recent is 'stochastic Loewner evolution', which is yielding new and exciting results. Much of this work is fairly mathematical, but the aim is always to derive results of physical significance, which can be tested against experiment or numerical simulation. Another aspect of my work in recent years has been the application of systematic field-theoretic renormalisation group methods to non-equilibrium critical behaviour, particularly in reaction-diffusion systems. I am also interested in learning about, and working on, the various phenomena associated with turbulence.

4.3 Disorder and coherence in quantum systems

J T Chalker

A range of problems is studied from condensed matter physics, with disorder or quantum coherence as common themes. Areas of current interest include: the quantum Hall effect and related phenomena involving electron systems in magnetic fields; mesoscopic conductors and nanostructures; links between quantum and classical problems involving systems with quenched disorder; and geometrically frustrated antiferromagnets.

The research frequently has a close link to experimental results, either from Oxford groups or from elsewhere, and typically depends on a mixture of physical arguments, analytic calculations and computer simulation.

4.4 Low-Dimensional Strongly Correlated Quantum Systems

F H L Essler

The importance of quantum fluctuations increases with decreasing dimensionality. As a result spatially anisotropic materials exhibit a variety of unusual physical properties such as quantum critical behaviour, spin-charge separation, quantum number fractionalisation and dimensional crossover. As theoretical concepts these phenomena are well established. However, how they manifest themselves in response functions accessible to experimental probes like inelastic neutron scattering, photoemission or inelastic x-ray scattering is not fully understood.

In recent years exact methods have been applied such as the form factor boostrap approach to quantum correlation functions in integrable quantum field theories, bosonization and the Bethe ansatz to determine dynamical response functions in a variety of quasi one dimensional antiferromagnets and Mott insulators. Much of this work is motivated by experiments carried out by groups at Oxford, Brookhaven, Oakridge and Baltimore.

4.5 Disordered systems, defects and exciton states, magnetism

R J Elliott

Research includes the study of excitations in disordered materials, particularly correlated particle motion and many-body effects. Specific problems relating to excitons in semiconductors, atomic diffusion and magnetic systems including non-equilibrium effects are being studied.

4.6 Complex co-operative behaviour due to disorder, frustration and kinetic constraints

D Sherrington

The combination of quenched randomness and competing interactions (frustration) often leads to very rich complex macroscopic behaviour in many-body systems, even when the constituent microscopic units are relatively simple. Examples occur in solids (e.g. spin glasses, randomly-pinned charge density waves), hard optimization problems (e.g. satisfiability problems in computer science, graph partitioning, routing), neural networks (as models of the brain or as new types of computers, operating as expert systems with associative and generalization facilities), biologically relevant processes (e.g. protein folding, evolution), economics (dynamically interacting agents), error-correcting codes and many more. Extensions apply to systems in which the interactions are also dynamically evolving and the systems self-organize, often in complex structures.

Techniques and concepts from statistical physics, both equilibrium and recently more particularly non-equilibrium, are being employed and extended to help unravel the key features of such systems, their similarities and differences, and their implications for fundamental understanding. The emphasis is principally on generic features and on the discovery and comprehension of new classes of behaviour and their physical and mathematical implications. Studies are dominantly analytic, based on generating functionals, and involving field-theoretic types of considerations, or master equations, but often guided or complemented by computer simulation and normally concerned with statistical relevance rather than special worst cases.

In fact complex behaviour can arise even in systems without imposed quenched disorder and significant study is now being directed to such systems in which glassy disorder and slow characteristic macroscopic behaviour, such as aging, occur due to non-equilibration, jamming and constrained dynamics, often pre-empting thermodynamic transitions or even when there are no thermodynamic transitions.

Studies include both systems with detailed balance (and, in principle, equilibrium descriptions within Boltzmann-type statistics) and systems without detailed balance (requiring fully dynamical treatment).

4.7 Collective behaviour in equilibrium and stochastic non-equilibrium systems; scaling, disorder, and glassy dynamics; econophysics

R B Stinchcombe

Minimal models and specially-developed techniques have in recent decades provided a fundamental understanding of the striking range of (nonlinear) phenomena exhibited by collective many-body systems in equilibrium. More difficult, and richer, are the non-equilibrium stochastic generalisations. These are familiar in everyday experience, in the rapid phase changes, turbulence, shocks, “crashes”, etc. exhibited in weather, traffic, earthquakes, crowd behaviour, financial markets, etc. Recent pioneering advances have resulted from representing non-equilibrium collective systems by lattice models and generalising equilibrium methods to treat them. These models apply directly to many physical systems and also crudely represent the everyday phenomena mentioned before. So their understanding has implications far beyond traditional physics. Our recent research on collective non-equilibrium models exploits mappings to (equilibrium) fermion or quantum spin systems. Applying traditional spin-to-fermion mappings, and developing new operator methods has led to some exact solutions. This approach continues, together with the application of more recently developed scaling techniques. Certain phenomena have been given special attention recently. Among them is anomalously slow “glassy” dynamics, and the behaviour of financial markets (where, particularly, a model has been introduced for limit-order markets), as well as the effects of disorder in both equilibrium and non-equilibrium systems.

4.8 Statistical mechanics

J M Yeomans

A variety of different problems in equilibrium and non-equilibrium statistical mechanics, soft condensed matter and fluid dynamics are being studied. We are interested in the static and dynamic properties of complex fluids such as polymers, liquid crystals and multiphase systems. The work ranges from problems with industrial application, through numerical investigation of fundamental physical properties, to analytic attempts to understand the underlying kinetic theory and the equilibrium and non-equilibrium properties of model fluids.

RESEARCH SUPPORT FACILITIES

1 Growth and characterisation of single crystals

R C C Ward

The Oxford Crystal Growth Group produces high quality single crystals for physics research both in Oxford and in other universities in the UK, using a variety of melt and solution growth techniques. Advanced equipment such as Czochralski pullers, Bridgman and top-seeded solution growth (TSSG) furnaces have been designed and built in the Clarendon. Special techniques have been developed for the growth of high-quality fluoride crystals under reactive HF atmospheres, for applications such as UV lasers and neutron diffraction. Crystals are characterised using X-ray diffraction techniques and by EPMA for elemental analysis.

The current major research interest of the group is the growth of advanced non-linear optical crystals, in particular KTP (potassium titanyl phosphate) analogues for frequency doubling, OPO and waveguide applications. Crystals of device quality and size are grown in a dedicated facility of five TSSG furnaces. Specific doping is used to optimise and tailor the optical properties (such as transmittance and damage threshold) of the KTP crystals, and optical and structural characterisation confirms their state-of-the-art performance. A collaborative EPSRC project with Warwick, St Andrews and Southampton Universities is aimed at the development and exploitation of KTP and its arsenate analogues in novel quasi-phase-matched NLO devices. This programme has involved setting up a complete chemical preparation process for highest quality arsenate starting materials.

2 High field magnet facility

H Jones

The Magnet Group manages the Clarendon facility, which provides the UK's highest magnetic fields.

The facilities we offer are:

i) A continuous field superconducting magnet up to 21.5 T in 40 mm, 18 T in 110 mm.

ii) Mobile superconducting magnet systems up to 18 T in 40 mm.

iii) Custom-built superconducting and conventional magnets dedicated to individual experiments.

iv) A new 3 station pulsed field facility based on a capacitor bank which will generate fields ~60 T, or more, over pulses ~10 – 100 ms.

v) Wire making equipment for the production of special conductors in-house.

Much magnet technology requires insulators, impregnants and adhesives which must operate in a range of hostile environments. The group has considerable expertise in this area and offers a department-wide service.

3 Cryogenic facilities

N Parker

The Cryogenic Facilities Group in the Clarendon Laboratory operates a 40 litre/hour Linde TCF20 liquefier which supplies liquid helium within the department and to other laboratories and organisations; annual production is 55,000 litres.

The group provides information and assistance on the design and construction of cryogenic equipment. In addition, our in-house service provides accurate calibration data for most types of cryogenic thermometer in the range 2–300 K.

4 Computing facilities in the Department of Physics

I C McArthur

The Department provides excellent computing facilities to support the research programme. Many different systems are used by research groups in the Department, depending upon their precise needs. However, all staff and students typically have an appropriate desktop system and access to very powerful and up-to-date systems for computation. Extensive use is made of both Linux/Unix and Microsoft Windows (in particular Windows 2000/XP). The Department employs 15 staff to provide system administration and user support. In most cases, there is a support person resident within each sub-department who is familiar with the specific needs of the research groups and who provides the first line of support.

High-speed access to the Internet is essential for research work in physics and the Department has installed state-of-the-art networking equipment to meet the ever-growing demands of its researchers. A very extensive local area network based mainly on switched 100 MHz Ethernet is used, with points in every laboratory and room. The Department's core network is based on Gigabit Ethernet and a 100Mb/s link to the University's gigabit-based network provides access to other University services (eg. the Libraries) and to the world wide Internet. The Department runs its own Email and Web servers in response to the huge volume of Internet traffic that occurs daily.

5 Physics Photographic Unit

I Campbell

The Unit is able to undertake and advise on a range of imaging techniques including visual aids, location, studio, scientific and technical photography, video recording, duplication and conversion. Much of the Unit output is via digital imaging, based on Apple Macintosh, but accepting input from PC and the local area network. Output available is to print, film or CD, with dye sublimation, inkjet and electrostatic printers used according to the quality and volume requirements. Poster printing and lamination is available up to A0.

Audio Visual facilities throughout Physics are managed by the PPU and larger lecture theatres are provided with data projectors and visualisers. Portable data projectors are available for smaller lecture and seminar rooms.

A videoconferencing facility is available on Level 5 of the Nuclear and Astrophysics Laboratory. This provides a comfortable, well-equipped room to facilitate meetings with external sites on a 24-hour basis.

Colour and black and white volume duplication is to A3 size and leaflet and booklet production facilities are available.

6 Photofabrication Techniques Unit

C W Band

The unit is well equipped to carry out a wide range of circuitry, both rigid and flexible. Currently the unit is specialising in the manufacture of high resolution, low mass cables. Thin components can also be chemically machined, eg slits, pinholes, springs and evaporation masks. Facilities are also available for the selective electroplating of precious and semi-precious metals. Low resolution chromium mask alignment plates can also be produced.

7 Central Electronics Group

J Fopma

The Central Electronics Group provides a wide range of electronics design, construction and repair services to support a diverse range of physics projects, from the large international particle physics experiments to small experiments in the teaching labs.

The group's facilities include:

- An active CAD office enabling design and simulation of Application Specific Integrated Circuits (ASIC's) and design of complex multi-layer Printed Circuit Boards (PCB's).
- A well-equipped electronics workshop enabling assembly and test of cables, modules and systems. This includes the Printed Circuit Board soldering and inspection of Ball Grid Array packages as well as the more regular Surface Mount and through hole mount packages.
- A live test room, equipped with instrumentation for instrument repair.
- A range of logic analysers, data and waveform generators, high speed digital oscilloscopes and general computer controlled instrumentation available for engineers and physicists for chip, board or system testing.

Other facilities provide Electro-Magnetic Compatibility (EMC) testing and an instrument loan pool. A team of engineers and technicians are able to provide expertise in a wide range of electronics related fields.

8 Mechanical design and workshops

W. Lau, T. Handford

The Design office is equipped with a comprehensive mechanical CAD and numerical analysis system which permits 2-D draughting, 3-D solid modelling, finite element structural and

Computational Fluid Dynamics analyses. The

workshops are equipped to manufacture experimental apparatus ranging from high precision instruments to large structural assemblies and provide continual support for experimental apparatus installed both locally and abroad. They are equipped with modern numerical control machine tools.

9 Thin film facility

C Goodwin

The facility has the equipment and expertise for the design, deposition, and measurement of a wide range of high quality thin film coatings. Many different materials can be deposited in single or multilayer stacks for use in the optical, electronic or aerospace fields. The coatings are designed using specialised computer software and then produced, in a class 10,000 cleanroom, using both thermal and electron beam evaporation techniques. Dual beam spectrophotometers are used to measure the finished coatings, and reverse engineering used to optimise them.

10 Semiconductor device and photo fabrication

R J Nicholas, C W Band

A purpose built suite of Class 10,000 clean rooms is available for the advanced fabrication of semiconductor and other devices. Patterning is performed using e-beam writing and photolithography. Structuring of the films is carried out with reactive ion-etching or wet chemical etching. A scanning electron miscroscope is also available. This technology is being applied to produce a wide range of semiconducting devices and detectors for particle physics and astrophysics.