Oxford Master Course
in
Mathematical and Theoretical Physics

Master of Mathematics and Physics (MMathPhys) and MSc in Mathematical and Theoretical Physics

Course Handbook

2016–2017

This handbook applies to students starting the Master of Mathematics and Physics (MMathPhys) or the MSc in Mathematical and Theoretical Physics in Michaelmas term 2016. The information in this handbook may be different for students starting in other years.

The Examination Regulations relating to this course are available at
http://www.admin.ox.ac.uk/examregs/.

If there is a conflict between the information in this handbook and the Examination Regulations then you should follow the Examinations Regulations. If you have any concerns please contact mathematical.physics@maths.ox.ac.uk.

The information in this handbook is accurate as at 1 October 2016, however it may be necessary for changes to be made in certain circumstances, as explained at **www.ox.ac.uk/coursechanges**. If such changes are made the department will publish a new version of this handbook together with a list of the changes and students will be informed.

Version 1.0

Welcome

Welcome to the Oxford Master Course in Mathematical and Theoretical Physics. Our course provides a high-level education in the areas of Theoretical Particle Physics/String Theory, Condensed Matter Theory, Theoretical Astrophysics/Fluids and Mathematical Foundations of Theoretical Physics up to the level of research.

As you are probably aware, there is considerable flexibility in designing your path through the course; you can decide to focus on one of the above areas or study more widely across areas. It is important that you consider your choices carefully. Consult the syllabi and the case studies in this handbook for more information and, if in doubt, talk to your personal tutor or an academic related to the programme.

For an advanced programme of this kind written examinations are not always the best form of assessment. You will find that the way we evaluate your work often correlates with the nature of the material. Typically, there will be formal written exams for the basic, foundational courses, other forms of assessment such as take-home exams or mini-projects for intermediate courses and a home-work completion requirement for advanced courses. There are certain constraints on assessment - for example you have to sit four written exams. Be sure that your course choices are consistent with these constraints. Also note that Trinity term is devoted to advanced courses and there is no designated revision period.

Passing exams is a necessary and important part of learning and education but we hope you agree that there is significantly more to it. Enthusiasm, engagement with the subject, the desire for deep and profound understanding is what truly motivates us and we hope this is how you will engage with the course. We wish you a successful, productive and insightful year.

Xenia de la Ossa and Andre Lukas

Contents

1 Introduction

This handbook contains important information about the Masters course in Mathematical and Theoretical Physics. It is intended as a guide and reference for you throughout the course. There are a number of other sources of information that you will need to refer to during your course and links to these are given below, together with a list of key contacts.

1.1 Key Sources of Information

Course website: http://mmathphys.physics.ox.ac.uk/
The course schedule, details of seminars and the online course handbook can all be found here.

Mathematical Institute website: http://www.maths.ox.ac.uk/

Department of Physics website: www.physics.ox.ac.uk

Examination Regulations: http://www.admin.ox.ac.uk/examregs/
The University's examination regulations govern all academic matters within the University and contain the general regulations for the conduct of University examinations, as well as specific regulations for each degree programme offered by the University.

Examination Conventions: http://mmathphys.physics.ox.ac.uk/students
The examination conventions for the course set out how each unit will be assessed and how the final degree classification will be derived from the marks obtained for the individual units.

Oxford Student website: http://www.ox.ac.uk/students
This website provides access to information, services and resources.

Oxford Student Handbook: http://www.admin.ox.ac.uk/proctors/info/pam/
This contains general information and guidance about studying at the University of Oxford, and gives you formal notification and explanation of the University's codes, regulations, policies and procedures.

College Handbook: The handbook for your college will be available on the college website.

1.2 Key contacts

Director of Studies Prof. Xenia de la Ossa (tel: (6)15326)
email: `Xenia.delaOssa@maths.ox.ac.uk`

Chair of JSC Prof. Andre Lukas (tel: (2)73953)
email: `andre.lukas@physics.ox.ac.uk`

Academic Administrator Mrs Charlotte Turner-Smith (tel: (6)15203)
email: `academic.administrator@maths.ox.ac.uk`

Deputy Academic Administrator Mrs Helen Lowe (tel: (6)15204)
email: `mathematical.physics@maths.ox.ac.uk`

Mathematical Institute Reception (tel: (2)73525)

Department of Physics Reception (tel: (2)72200)

1.3 The Academic Year

The course lasts three terms, from the beginning of October to the end of the following June. Some work is carried out in the vacations.

For the academic year 2016-2017, the course begins with an induction on 4 October 2016. The dates of the University Full Terms for the Academic Year 2016–2017 are:

MT = Michaelmas Term 2016: 10 October – 2 December
HT = Hilary Term 2016: 16 January – 11 March
TT = Trinity Term 2015: 24 April – 16 June

A calendar of important dates is given in Appendix A.

1.4 Finding Your Way Around

Teaching for the course will take place in the Mathematical Institute (**http://www.maths.ox.ac.uk/about-us/travel-maps**) and in the Denys Wilkinson Building or in the Clarendon Building of the Department of Physics (**http://www.physics.ox.ac.uk/contact/Physicsmap.pdf**). To enter the Denys Wilkinson Building, go up the wide concrete steps from Keble Road; turn left at the top and the entrance is facing you. The main entrance to the Clarendon in on Parks Road, next to the University Parks.

A searchable, interactive map of all college, department and libraries can be found at **http://www.ox.ac.uk/visitors/maps-and-directions/searchable-map**.

2 The MSc Course

2.1 Overview

The Master's Course in Mathematical and Theoretical Physics is offered in two modes, the MMathPhys for Oxford students and the MSc for students from outside Oxford. The academic content is identical for both modes. If you are an Oxford MPhys, MMath or MPhysPhil student, who transfers to the MMathPhys you will graduate as a "Master of Mathematical and Theoretical Physics" with a double classification consisting of the BA degree class in your original subject and an MMathPhys degree class. If you are a student on the MSc course, you will graduate with an "MSc in Mathematical and Theoretical Physics."

These qualifications may be compared to national standards for higher education qualifications through the Framework for Higher Education Qualifications (FHEQ). The University awards framework (UAF) maps the awards of the University against the levels of the FHEQ. The FHEQ level for both the MMathPhys course and MSc course is 7. The relevant subject benchmark statements for the course, which set out expectations about standards of degrees in a given subject area, are Physics & Astronomy (QAA 2008) and Mathematics, Statistics & Operational Research (QAA 2015).

2.2 Aims

The Oxford Master's Course in Mathematical and Theoretical Physics aims to provide students with a high-level, internationally competitive training in mathematical and theoretical physics, right up to the level of modern research in the area.

As a graduate of this programme you will be in a prime position to compete for research degree places in an area of Theoretical and Mathematical Physics at leading research universities in the UK or overseas; or to pursue a research-related career, based on the acquired high-level ability in mathematics and its applications to physical systems, outside academia.

2.3 Learning Outcomes

During the course you will develop a knowledge and understanding of:

- Theoretical and Mathematical Physics, focusing on one of the areas of Theoretical Particle Physics, Theoretical Condensed Matter Physics, Theoretical Astrophysics/Fluids, or studying across these areas.
- A broad range of physical phenomena and their description within Theoretical Physics.
- A wide range of advanced mathematical techniques and how they are applied in Theoretical Physics.

You will also have the opportunity to develop the following skills.

Intellectual Skills

- An appreciation of the principles of Theoretical and Mathematical Physics and their application to natural phenomena.
- The ability to model physical phenomena and deploy a wide range of mathematical physics methods for their description.

- A working knowledge of high-level mathematical methods and their application to systems in physics and beyond.

Practical Skills

- Ability to apply mathematical methods to practical problems.
- Ability to construct, write-up and communicate logical arguments of some complexity.

Transferable Skills

- Ability solve problems effectively and to apply high-level mathematical methods to a wide range of problems.
- Ability to manage your time and to acquire a complex body of knowledge in a limited time.
- Ability to manage your own learning and study for research or other professional qualifications.

2.4 Course Structure

The programme consists of a large array of lecture courses covering the main areas of modern Theoretical/Mathematical Physics and Applied Mathematics. The courses are subdivided into the following *strands:*

- Quantum Field Theory, Particle Physics and String Theory
- Theoretical Condensed Matter Physics,
- Theoretical Astrophysics, Plasma Physics and Physics of Continuous Media.
- Mathematical Foundations of Theoretical Physics

As various areas of Theoretical and Mathematical Physics are in fact, interconnected, routed in universal principles and thrive on ideas that cross any sub-field boundaries, a number of courses are shared between the three strands and emphasise the unity of the subject. This applies especially to the *foundational courses* offered in Michaelmas term. These are followed by increasingly specialised courses in Hilary and Trinity terms, although those too will strive to make connections between subject areas.

There are no compulsory courses and you will thus be able to choose a path reflecting your intellectual tastes or career choices; Appendix C gives examples of different pathways through the course. An overview of the courses can be found in the table accompanying this section. Detailed synopsis for each course can be found in Appendix B and a table providing details of the assessment method for each course can be found in Appendix A of the examination conventions.

In addition to the courses listed in the table, which are offered explicitly as part of the MMathPhys/MSc programme, you will also be allowed to choose a maximum of three-units worth of MMath Part C (see **http://www.maths.ox.ac.uk/members/students/undergraduate-courses/teaching-and-learning/**) or MPhys Part C (see **http://www.physics.ox.ac.uk/lectures/**) lecture courses that are not listed here, subject to approval by the Director of Studies. Approval should be sought by Friday of week 4 of Michaelmas term.

You will be required to undertake 10 units, with 1 unit corresponding to 16 hours of lectures. This means that 16-hour lecture courses count as one unit, while, for example, 24-hour lecture courses count as 1.5 units. More specifically you are required to offer:

(a) **four units that are assessed by written invigilated exams,**

(b) **three units that are assessed by written invigilated exams or in other ways,**

(c) **three other units (which may be from courses with homework completion requirement only or from assessed courses),**

(d) **an oral presentation.**

One or two of the 10 units in (b) or (c) can be replaced by a dissertation. There are no other formal constraints on course choices and students are otherwise free to design their own pathways (although paying close attention to the guidance offered is strongly recommended). Note however that you should be careful about the number of units you undertake each term, and that taking too many units in Trinity term may be difficult as exams start on week 6. In practice it may be difficult to fit in more than 12 units in total. Please note that it is your responsibility to ensure that you fulfil the requirements for the overall number of units and the number of assessed units. The modes of assessment and details on completion requirements for all courses are provided in Appendix A of the exam conventions.

You will be offered detailed academic guidance from the Director of Studies or an Academic Adviser designated by the Director of Studies on choosing an individual path suitable for you. Course lecturers will also advise on the recommended background for their courses or possible follow-up courses you might wish to choose.

Legend for fonts, colours and superscripts in the Table:

Bold: a foundational course;

Plain: an interdisciplinary course shared between strands;

Italic: a course special to a particular strand;

Red$^{(PU:NN)}$: a course also taught (in some cases in part) as a Part C course in Physics, NN is its number;

Blue$^{(MU:NNN)}$: a course also taught as a Part B or C course in Mathematics, NNN is its number;

Purple$^{(MG)}$: a course also taught as a PG course in Mathematics;

Black: an MMathPhys/MSc course, also taught as a PG course in Physics;

$^{(*)}$ a course that may not be available every year.

Overview of Lecture Courses			
	Theoretical Particle Physics	*Theoretical Condensed Matter Physics*	*Theor. Astrophysics, Plasma Physics & Physics of Continuous Media*
MT	**Quantum Field Theory** (24)		
		Statistical Mechanics$^{(MU:C5.3)}$ (16)	
		Advanced Quant. Theory$^{(PU:C6)}$ (20)	
		Nonequilibrium Statistical Physics$^{(PU:C6)}$ (4)	
	Topological Quantum Theory (16)		
		Kinetic Theory (24)	
			Rad. Proc. & High Energy Astro. (20)
	Gen. Relativity I$^{(MU:C7.5)}$ (16)	⇐ ⇒	**Gen. Relativity I**$^{(MU:C7.5)}$ (16)
	Perturbation Methods$^{(MU:C5.5)}$ **(16)**		
	Numerical Linear Algebra$^{(MU:C6.1)}$ (16)		
	Groups and Representations (24)		
	Algebraic Topology$^{(MU:C3.1)}$ *(16)*		
	Differential Geometry $^{(MU:C3.3)}$ (16)	⇐ ⇒	Differential Geometry $^{(MU:C3.3)}$ (16)
	Algebraic Geometry$^{(MU:C3.4)}$ *(16)*		
HT		Advanced Fluid Dynamics (16)	
		Soft Matter Physics (16)	
		Nonequilibrium Statistical Physics$^{(PU:C6)}$ (20)	
	Advanced QFT (24)	*Quant. Matter (16)*	
	String Theory I$^{(MG)}$ *(16)*	*Networks*$^{(MU:C5.4)}$ *(16)*	*Collisionless Plasma Physics (16)*
	Supersymmetry & Sugra (24)		*Galactic & Planetary Dyn. (16)*
			Geophys. Fluid Dynamics (16)
			Astro. Gas Dynamics$^{(PU:C1)}$ *(10)*
	Intro to Quantum Information $^{(MU:C7.4)}$ (16)		
	Gen. Relativity II$^{(MU:C7.6)}$ (16)	⇐ ⇒	Gen. Relativity II$^{(MU:C7.6)}$ (16)
	Cosmology (16)	⇐ ⇒	Cosmology (16)
	Nonpert. Meth. in QFT (8)		
	Applied Complex Variables$^{(MU:C5.6)}$ (16)		
	Geom. Group Th.$^{(MU:C3.2)}$ *(16)*		
TT	Conformal Field Theory $^{(*)}$ (16)		
	Introduction to Gauge-String Duality (16)		
		Topics in Soft & Active Matter Physics (8)	
		Complex Systems$^{(MG,*)}$ (16)	
	String Theory II$^{(MG,*)}$ *(16)*		
	The Standard Model (16)	*Topics in Quant. CMP (8)*	*Collisional Plasma Physics (16)*
	Beyond the St. Model (16)		
	Nonpert. Meth. in QFT (8)		*Astro. Gas Dynamics*$^{(PU:C1)}$ *(10)*
	Astroparticle Phys.$^{(*)}$ (16)	⇐ ⇒	Astroparticle Phys.$^{(*)}$ (16)
	QFT in Curved Space$^{(*)}$ (16)	⇐ ⇒	QFT in Curved Space$^{(*)}$ (16)
	Dissertation, replacing one or two 16-hour lecture course		

3 Teaching and Learning

3.1 Organisation of Teaching

Teaching for the course will be provided jointly by the Department of Physics and the Mathematical Institute through lectures and classes. In addition, students undertaking a dissertation will have supervision meetings with their dissertation supervisor.

3.2 Lectures

Depending on the options you take you will have between 6-8 hours of lectures per week. The lecture timetable for each term will be made available on the course website **http://mmathphys.physics.ox.ac.uk/**.

Course Material

Course material, such as lecture notes and problem sheets, will be published on the Mathematical Institute's website and the Department of Physics' website. Students should follow the links to the appropriate pages from the lecture schedule on the course website.

3.3 Classes

Lecture courses will normally be accompanied by problem sets and weekly or fortnightly problem classes. Classes will usually contain 8–10 students. For most courses you will need to sign-up for the set of classes you wish to attend at the start of each term, and this is usually done via an online sign-up system. You will be sent an email in week 0 alerting you that class registration is open and providing you with details of the registration process. You can find out which class you have been allocated to by looking at the class lists (**https://minerva.maths.ox.ac.uk/perl/classlists.pl**). For classes accompanying courses taught by the Physics Department, particularly those part of the undergraduate MPhys course, you will be provided information on the classes and sign-up process by the course co-ordinator.

Before each class you will need to submit your problem sheet to the class teaching assistant for marking. For courses for which there is a homework completion requirement you will need to submit your problem sheet online (following the process described below). For all other courses you should submit your problems sheets as instructed by the class tutor. The table in Appendix A of the examination conventions indicates for which courses there is a homework completion requirement.

You should always submit your problem sheet before the stated deadline. However, this is particularly important for courses which have a homework completion requirement as late problem sheets will only be accepted in exceptional circumstances. Please see section 3.4 of the examination conventions for further information.

Online Submission Process

- If you have hand-written your problem sheet, you can use the photocopiers in the Mathematical Institute or University libraries to scan your work.

- Go to **https://courses.maths.ox.ac.uk/** and log in using your Mathematical Institute IT account or University SSO.
- Select the course your are submitting work for from the list of courses on the homepage.
- Click on the assignments tab.
- Upload your problem sheet.
- Press save to submit your work.
- You will receive an email confirming that your work has been submitted successfully.

3.4 Dissertations

You may opt to offer a dissertation as one, or with special permission two, of your ten units. A dissertation offers a substantial opportunity for independent study and research, and would be undertaken under the guidance of a member of the Department of Physics or the Mathematical Institute. A dissertation involves investigating and then presenting in writing a particular area of Mathematical Physics or Theoretical Physics; you would not be required (but may) obtain original results. A list of possible dissertation topics is given in Appendix D but you are not limited to this list and may propose your own topic instead.

If you intend to undertake a dissertation you will need to notify the Joint Supervisory Committee for the course by Monday of week 2 of Hilary term. As such you are advised to start thinking about your dissertation and make initial contact with potential supervisors during Michaelmas term. You should submit to the Joint Supervisory Committee a typed abstract of at least 100 words (but no more than one A4 sheet) together with a list of the main references you will be using. If you wish to offer a double unit dissertation, you should obtain permission for the Course Director (by emailing mathematical.physics@maths.ox.ac.uk) prior to submitting your abstract. The Committee will consider all abstracts at its meeting in week 3 of Hilary term and communicate its decision to students as soon as possible thereafter (abstracts submitted before the end of Michaelmas term will be considered earlier). The submission deadline for dissertations is noon on Monday, week 5 of Trinity term.

You should plan on beginning work on your dissertation soon after your abstract has been approved. You are advised to bear in mind that you will need to use your time in the Easter vacation and early Trinity term wisely to balance preparing for the Trinity term exams, working on your dissertation, and completing work for other courses you may be taking.

Your supervisor will read and provide feedback on the initial draft of your dissertation (provided that it is submitted to them in good time!).

The submitted dissertation should conform to the following points.

- The dissertation must include an abstract and a bibliography.
- The dissertation must be word-processed and have a font size of 12pt.
- The text should be double spaced and the dissertation printed single-sided.
- The dissertation should be spiral-bound or soft-bound.
- The dissertation should have a title page which includes the following:
  - the title of dissertation,
  - the candidate's examination number,

  - the title of the candidate's degree course,
  - the term and year of submission.

- Its length should not exceed 30 pages for a single unit and 60 pages for a double unit. The page count may exclude any table of contents, diagrams, tables, bibliography and the texts of computer programs. However any footnotes and appendices must be included.

3.5 Advice on Teaching and Learning Matters

There are a number of people you can consult for advice on teaching and learning matters. Academic advisors will be appointed for all students at the start of the course and will be available for consultation on any academic matter. Students can also seek guidance on academic matters from their college personal tutor. All students will receive academic guidance from the Director of Studies.

If you have any issues with teaching or supervision please raise these as soon as possible so that they can be addressed promptly. Details of who to contact are provided in Section **??** Complaints and Appeals.

3.6 Skills and Learning Development

Expectations of Study

You are responsible for your own academic progress. Therefore, in addition to the formal teaching you receive through lectures, classes and dissertation tutorials, you will be expected to undertake a significant amount of self-directed, independent study both during term time and in the vacations. You are advised to read the University's guidance on undertaking paid work at **http://www.ox.ac.uk/students/life/experience**.

Your academic process will be monitored by your academic advisor and also your college tutor. College tutors will receive reports from the class tutors for the classes you attend. In addition, academic advisors of MSc students will submit termly reports on their student's progress via the Graduate Supervision System. These reports are reviewed by the Director of Studies. If you are concerned about your academic progress please contact your college tutor, academic advisor or the Director of Studies.

University Lectures and Departmental Seminars

University lectures in all subjects are open to all students. A consolidated lecture list is available on the University website at: **http://www.ox.ac.uk/students/academic/lectures/**.

Seminars and colloquia given in the Mathematical Institute and Physics Department, often by mathematicians and physicists of international repute, are announced on the departmental notice boards (**https://www.maths.ox.ac.uk/events/list** and **http://www2.physics.ox.ac.uk/research/rudolf-peierls-centre-for-theoretical-physics/seminars**); you are encouraged to attend any which interest you.

Study Skills

Much of the advice and training in study skills will come in the regular class teaching you receive. A wide range of information and training materials are available to help you develop your academic skills – including time management, research and library skills, referencing, revision skill and academic writing – through the Oxford Student website: **http://www.ox.ac.uk/students/academic/guidance/skills**.

3.7 Key Teaching Links

Lecture Timetable: http://mmathphys.physics.ox.ac.uk/course-schedule

Class Lists: https://minerva.maths.ox.ac.uk/perl/classlists.pl

Physics Class Information: Follow links to course pages from **https://mmathphys.physics.ox.ac.uk/course-schedule**

Problem Sheet Submission: https://www0.maths.ox.ac.uk/node/add/course-work

Project Application Form: http://mmathphys.physics.ox.ac.uk/students

Project Guidance Notes: http://mmathphys.physics.ox.ac.uk/students

4 Examinations and Assessments

4.1 Assessment of the Course

All of the units you undertake will have either a component of formal assessment (written invigilated exam, take-home exam, mini-project or dissertation) or a homework completion requirement. Each unit will be assessed by the method most suited to the material being taught. The table in the examination conventions indicates which courses are assessed and by which method and it indicates which courses have a homework completion required. The examinations are governed by the University's Examination Regulations and the course examination conventions.

4.2 Examination Conventions

The examination conventions for the course are the formal record of the specific assessment standards for the course. They set out how each unit will be assessed and how the final degree classification will be derived from the marks obtained for the individual units. They include information on marking scales, marking and classification criteria, scaling of marks, formative feedback, resits and penalties for late submission. The examination conventions for 2016–17 can be found on the course website at **http://mmathphys.physics.ox.ac.uk/**.

4.3 Examination Entries

You will need to formally enter for the units you wish to be assessed on, including those courses which only have a homework completion requirement, by completing an examination entry form. This is done online through Student Self Service (**https://evision.ox.ac.uk/**) and further information on the process can be found at **http://www.ox.ac.uk/students/academic/exams/entry**. For this course there will be three examination entry dates:
Friday 4th November, week 4, Michaelmas term for Michaelmas term courses with Michaelmas term submissions and courses examined by invigilated written examination in Hilary term;
Friday 27th January, week 2, Hilary term for Hilary term courses with Hilary term submissions and all courses assessed by invigilated written examination in Trinity term.
Friday 28th April, week 1, Trinity term for Trinity term courses and the dissertation option.

When completing your examination entry you should try to ensure that the decisions you make are as final as possible. However, if you subsequently change your mind about which courses you would like to be assessed on, then it is possible to make changes to your entry. To change an option after the examination entry deadline has passed you must apply for permission in writing through your senior tutor or other college officer using the change of options form available from your college office. You will need to pay a fee for making a late change to your examination entry.

If you have entered for assessments in additional courses (beyond the required ten units) but subsequently decide not to take the additional assessments, then you should inform your college office. You must do this prior to either the examination date for written examinations or the submission date for coursework.

4.4 Examination Dates and Submission Deadlines

The calendar of important dates (Appendix A) gives the expected start dates for the invigilated written examinations and coursework submission deadlines. The examination timetable for invigilated written

examinations will be set by the Examination Schools and published online at:
http://www.ox.ac.uk/students/academic/exams/timetables.

4.5 Preparation and Submission of Coursework

4.5.1 Mini-Projects and Take-Home Examinations

Some units will be assessed wholly or partially by submitted work. This will take one of two forms: mini-project or take-home examination. The deadline for the submission of the assessment for each unit is given in the table included in the examination conventions.

The examiners will send out notices to candidates detailing where your work should be submitted, how many copies you should submit, and what format your submission should be in (e.g. handwritten or word-processed). For certain courses candidates will be required to submit an electronic copy. Details of the courses to which this applies, and instructions on the online submission process will be included in the notice to candidates.

It is vital that you submit your work by the given deadline as any late submission will be reported to the Proctors and a late submission penalty may be applied (see section 5 in the examination conventions). Please see the examination conventions and the Oxford Student website (**http://www.ox.ac.uk/students/academic/exams/submission**) for advice on what to do if you are unable to submit your work on time due to medical emergency or other urgent cause.

4.5.2 Dissertation

The deadline for submission of the dissertation is 12noon on Monday of week 5, Trinity term. Students will be required to submit three bound copies of their dissertation, together with a declaration of authorship form, to the Chair of Examiners, Mathematical and Theoretical Physics, c/o Examination Schools, High Street, Oxford, OX1 4BG. Please note the information in section 4.5.1 regarding the importance of submitting your work on time.

4.5.3 Plagiarism

Plagiarism is presenting someone else's work or ideas as your own, with or without their consent, by incorporating it into your work without full acknowledgement. All published and unpublished material, whether in manuscript, printed or electronic form, is covered under this definition. Plagiarism may be intentional or reckless, or unintentional. Under the regulations for examinations, intentional or reckless plagiarism is a disciplinary offence. Please see the University's guidance on plagiarism
http://www.ox.ac.uk/students/academic/guidance/skills/plagiarism for further information.

4.6 Sitting Invigilated Written Examinations

Information on (a) the standards of conduct expected in examinations and (b) what to do if you would like examiners to be aware of any factors that may have affected your performance before or during an examination (such as illness, accident or bereavement) are available on the Oxford Student website (**http://www.ox.ac.uk/students/academic/exams**) and in Section 8.2 of the examination conventions.

4.7 Oral Presentation

All students are required to give an oral presentation on a specialist topic in Trinity term. See Section 3.5 of the examination conventions for further details. The oral presentations will be organised by a coordinator appointed by the Joint Supervisory Committee for the MMathPhys/MScMTP.

A list of possible topics is given in Appendix E. Students undertaking a dissertation must give their oral presentation on the subject of their dissertation. Students may also approach the coordinator to propose their own topics. Students are asked to send the title of their intended topic, together with a short abstract to the coordinator by Monday of week 8 of Hilary term (for students offering a dissertation this forms part of the dissertation application process and they do not need to make a separate submission).

The presentation should not be longer than 20 minutes and there will be a 10 minute discussion session after the presentation. You are free to choose whether you want to give a blackboard presentation or use slides. Further details will be circulated to all students by email in Hilary term.

4.8 Examination Prizes

A prize may be awarded by the Examiners for excellence in examination for the Master of Mathematics and Physics (MMathPhys) or MSc in Mathematical and Theoretical Physics. The assessors of a dissertation that, in their view, shows particular originality and/or insight may recommend to the Examiners that this dissertation be given a commendation. A prize may be awarded by the examiners for the best dissertation.

4.9 Key Assessment Links

Examination Regulations: http://www.admin.ox.ac.uk/examregs/

Examination Timetables: http://www.ox.ac.uk/students/academic/exams/timetables

Online Submission: https://courses.maths.ox.ac.uk/

Past examination papers: https://mmathphys.physics.ox.ac.uk/past-examination-papers

Past examiners reports: http://mmathphys.physics.ox.ac.uk/students

5 Resources and Facilities

5.1 Departmental Work and Social Spaces

You will be able to use the computers and desks in the Mezzanine Study Room to work within the Mathematical Institute. The study room has power sockets for students wishing to use their own laptops and there is wi-fi throughout the building

The Institute's café is also located on the mezzanine level and has seating and tables for 100. The café serves drinks, snacks and meals from 8.30–16.15. Students are also welcome to use the Common Room on the first floor.

5.2 Libraries

Whitehead Library, Mathematical Institute

Website: **http://www.maths.ox.ac.uk/members/library**
Contact: Ms Cathy Hunt (Librarian) — `library@maths.ox.ac.uk`
The Whitehead Library holds material covering mathematical topics at postgraduate and research level, including mathematical physics. It is primarily for the use of current postgraduate students and academic staff of the Mathematical Institute.

Your University Card will have been activated to open the library door and will give you 24/7 access.

Books taken out of the library must be checked-out on the SOLO computer loan system at the terminal in the library. Please note that books are not allowed to be taken away from Oxford.

Theoretical Physics Collection, Department of Physics

Website:**http://www2.physics.ox.ac.uk/research/rudolf-peierls-centre-for-theoretical-physics**

Radcliffe Science Library (RSL)

Website:**http://www.bodleian.ox.ac.uk/science/**
The Radcliffe Science Library is the Science Library of the Bodleian and includes mathematics books at graduate and research level.

Information about all Oxford Libraries can be found at:
http://www.bodleian.ox.ac.uk/libraries/libraries.

5.3 Computing Facilities

Information regarding the University's IT Services can be found at **http://www.it.ox.ac.uk/**.

IT and Email accounts

At the departmental induction session you will be given a Mathematical Institute IT account and email address. The email address will be of the format `firstname.lastname@maths.ox.ac.uk`.

It is important that you either read this email regularly or set up a forward from it to an account which you do read regularly.

MSc students will also receive a University 'single-sign-on' IT account. This will have an email address associated with it which will be of the format

`firstname.lastname@college.ox.ac.uk`.

It is important that students either read this email regularly or set up a forward from it to an account which they do read regularly. MMathPhys students will retain the account they were issued with at the start of their degree.

For further information about Departmental IT matters, including rules and regulations surrounding the use of IT facilities, please see **http://www.maths.ox.ac.uk/members/it**

You will have access to various licences for further details go to **http://www.maths.ox.ac.uk/members/it/software-personal-machines**.

5.4 Careers Service

Careers guidance is provided by the *Careers Service* (**http://www.careers.ox.ac.uk/**), which also provides training in writing applications, interview techniques and analysis of transferable skills. The Careers Service provides information about occupations and employers, and advertises work experience opportunities.

In addition to its general programme, the Careers Service runs an annual 'Jobs for Mathematicians' half-day, in collaboration with the Mathematical Institute. At this event there are talks from alumni working in various industries and a talk for those interesting in continuing on to further postgraduate study. Further information about postgraduate study opportunities at the Mathematical Institute can be found at **http://www.maths.ox.ac.uk/study-here/postgraduate-study** and at **http://www2.physics.ox.ac.uk/study-here/postgraduates** for opportunities in the Department of Physics.

6 Student Representation and Feedback

6.1 Student Representation

Students will be able to nominate a representative to sit on the Joint Supervisory Committee (JSC) which oversees the course. Volunteers will be sought at the Induction Session and an election held if necessary. The student representative will be able to raise matters with the JSC on behalf of the cohort.

6.2 Consultative Committee for Graduates – Mathematics

The Consultative Committee for Graduates meets regularly once a term and discusses any matters that graduate students wish to raise. Students will be invited to nominate a representative to serve as the Mathematics and Physics rep on this committee via email in Michaelmas term.

6.3 The Physics Joint Consultative Committee

The Physics Joint Consultative Committee (PJCC) has elected undergraduate members who meet twice in MT and HT, and once in TT to discuss both academic and administrative matters with academic staff representatives. See **http://www.physics.ox.ac.uk/pjcc/** for more information.

6.4 Divisional and University Representatives

The MPLS Division also runs a divisional Undergraduate Joint Consultative Forum, a divisional Graduate Joint Consultative Forum, and is establishing a Joint Consultative Forum for Graduate Taught Courses. Each Forum is chaired by the senior MPLS Academic who is responsible for that area across the Division, an undergraduate or graduate representative from each department, the undergraduate or graduate representative on the Academic Committee and Divisional Board, and the Oxford Union Student Union (OUSU) Vice-President (Access and Academic Affairs) or Vice-President (Graduates).

Student representative sitting on the MPLS Divisional Board are selected through a process organised by OUSU. Details can be found on the OUSU website along with information about student representation at the University level.

6.5 Opportunities to Provide Feedback

Students will be asked to complete questionnaires evaluating the teaching received for each unit. Please take time to complete these as your feedback is valuable for future course planning.

MSc students, like all students on matriculated courses, will be surveyed on all aspects of their course (learning, living, pastoral support, college) through the annual Student Barometer. Previous results can be viewed by students, staff and the general public at: **www.ox.ac.uk/students/life/feedback**. MMathPhys students, as final year undergraduates, will be surveyed through the National Student Survey instead. Results from previous NSS can be found at **www.unistats.com**.

6.6 Key Student Representation Links

CCG: http://www.maths.ox.ac.uk/members/students/postgraduate-courses/doctor-philosophy/

consultative-committee-graduates. Minutes of meetings and list of student representatives.

OUSU: http://ousu.org/

University Surveys: http://www.ox.ac.uk/students/life/feedback

7 Student Support and Academic Policies

7.1 Where to Find Help

Generally speaking for graduate students departments are the main source of academic support and colleges are the main source of pastoral support. For undergraduate students colleges also play a key role in providing academic support.

Every college has their own systems of support for students, please refer to your college handbook or website for more information on who to contact and what support is available through your college.

Details of the wide range of sources of support available more widely in the University are available from the Oxford Student website (**http://www.ox.ac.uk/students/welfare**), including in relation to mental and physical health and disability.

7.2 Complaints and academic appeals within the Department of Physics and the Mathematical Institute

The University, the Mathematical, Physical and Life Sciences Division, the Department of Physics and the Mathematical Institute all hope that provision made for students at all stages of their course of study will result in no need for complaints (about that provision) or appeals (against the outcomes of any form of assessment).

Where such a need arises, an informal discussion with the person immediately responsible for the issue that you wish to complain about (and who may not be one of the individuals identified below) is often the simplest way to achieve a satisfactory resolution.

Many sources of advice are available from colleges, faculties/departments and bodies like the Counselling Service or the OUSU Student Advice Service, which have extensive experience in advising students. You may wish to take advice from one of those sources before pursuing your complaint.

General areas of concern about provision affecting students as a whole should be raised through Joint Consultative Committees or via student representation on the faculty/departments committees.

Complaints

If your concern or complaint relates to teaching or other provision made by the faculty/department, then you should raise it with Director of Undergraduate Studies (Dr Richard Earl (Maths), Prof Jonathan Jones (Physics)) or with the Director of Graduate Studies (Prof. Andreas Muench (Maths)) as appropriate. Complaints about departmental facilities should be made to the Departmental administrator/Head of Physical Resources (Dr Keith Gillow (Maths), Mr Malcom Bradbury (Physics)). If you feel unable to approach one of those individuals, you may contact the Head of Department (Prof. Martin Bridson (Maths), Professor John Wheater (Physics)). The officer concerned will attempt to resolve your concern/complaint informally.

If you are dissatisfied with the outcome, you may take your concern further by making a formal complaint to the Proctors under the University Student Complaints Procedure **https://www.ox.ac.uk/students/academic/complaints**.

If your concern or complaint relates to teaching or other provision made by your college, you should raise it either with your tutor or with one of the college officers, Senior Tutor, Tutor for Graduates (as appropriate). Your college will also be able to explain how to take your complaint further if you are dissatisfied with the outcome of its consideration.

Academic Appeals

An academic appeal is an appeal against the decision of an academic body (e.g. boards of examiners, transfer and confirmation decisions etc.), on grounds such as procedural error or evidence of bias. There is no right of appeal against academic judgement. If you have any concerns about your assessment process or outcome it is advisable to discuss these first informally with your subject or college tutor, Senior Tutor, course director, director of studies, supervisor or college or departmental administrator as appropriate. They will be able to explain the assessment process that was undertaken and may be able to address your concerns. Queries must not be raised directly with the examiners. If you still have concerns you can make a formal appeal to the Proctors who will consider appeals under the University Academic Appeals Procedure (**https://www.ox.ac.uk/students/academic/complaints**).

7.3 Student Societies

There are number of Mathematics and Physics student societies which you may like to join. Details of the main societies are given below. In addition there are also over 200 clubs and societies covering a wide range of interest which you may join or attend. A full list is available at **http://www.ox.ac.uk/students/life/clubs/list**.

Invariants

The Oxford University's student society for Mathematics. The society promotes Maths and hosts informal lectures, often given by leading mathematicians. Website: **http://www.invariants.org.uk/**.

Mirzakhani Society

The Mirzakhani Society is a society aimed at supporting women in Oxford who are studying maths. Their main event is 'Sip and Solve' which happens once a week, tea and cake are provided, and women are encouraged to come along to do problem sheets. Contact: `mirzakhanisociety@gmail.com`.

The Oxford University Physics Society

The Oxford University Physics Society (PhysSoc) is a student society that exists to promote and encourage an interest in Physics in and around Oxford University. PhysSoc hosts talks most weeks during termtime in the Physics Department, often by leading experts and also holds social events which are a great opportunity to get to know others with an interest in all things Physics. Website: **http://www.physsoc.co.uk/**.

7.4 University Policies

The University has a wide range of policies and regulations that apply to students. These are easily accessible through the A–Z of University regulations, codes of conduct and policies available at **http://www.ox.ac.uk/students/academic/regulations/a-z**. Particular attention is drawn to the following University policies.

Equal Opportunities Statement:
http://www.admin.ox.ac.uk/eop/missionstatement/integratedequalitypolicy/

Intellectual Property Rights: www.admin.ox.ac.uk/rso/ip

Code on Harassment: http://www.admin.ox.ac.uk/eop/harassmentadvice/policyandprocedure/

Policy on Plagiarism: http://www.ox.ac.uk/students/academic/guidance/skills/plagiarism

7.5 Departmental Safety Policies

You are urged to act at all times responsibly, and with a proper care for your own safety and that of others. Departmental statements of safety policy are posted in all departments, and you must comply with them. Students should note that they (and others entering onto departmental premises or who are involved in departmental activities) are responsible for exercising care in relation to themselves and others who may be affected by their actions.

In the Mathematical Institute accidents should be reported immediately to reception, telephone 73525, who keep the accident book. There is a first aid room located on the ground floor of the South wing. If you require access to this room please report to reception.

Each lecture theatre has its own proper escape route and you are urged to familiarise yourself with these. Those for the Mathematical Institute lecture and seminar rooms, are set out online at **http://www.maths.ox.ac.uk/members/building-information/security-safety-and-reporting-building-issues**. In the case of evacuation of the lecture theatre give heed to the instructions of the lecturer.

7.6 Key Student Support Links and Contacts

Disability Co-ordinator (Mathematics):
Charlotte Turner-Smith (`academic.administrator@maths.ox.ac.uk`)

Information on Disability and Accessibility: https://www.maths.ox.ac.uk/members/policies/disability
https://www.maths.ox.ac.uk/members/building-information/accessibility

Disability Co-ordinator (Physics): Carrie Leonard-McIntyre (`c.leonard-mcintyre@physics.ox.ac.uk`)

University's Disability Advisory Service: http://www.ox.ac.uk/students/welfare/disability

Counselling Service: (tel: (2)70300) email: `counselling@admin.ox.ac.uk`

Proctors' Office: (tel: (2)70090) email: `proctors.office@proctors.ox.ac.uk`

Departmental Harassment Advisors: names and contact details displayed in Mezzanine Study Room.

Oxford University Student Union, Vice President (Welfare):
(tel: (2)88452) email: `welfare@ousu.ox.ac.uk`

A Course Calendar

Michaelmas Term

Tuesday 4th October, 10am (week 0)	Induction and welcome party
Friday 7th October, 11.30am (week 0)	Introduction to Michaelmas term courses
Monday 10th October (week 1)	Michaelmas term lectures begin
Week 4	Examinations briefing and afternoon tea
Friday 4th November (week 4)	Examination entry for Michaelmas term courses with Michaelmas term submission and all courses assessed by invigilated written examination in Hilary term
Monday 28th November (week 8)	Michaelmas term mini-projects released
Friday 2nd December (week 8)	Michaelmas term lectures end
Monday 19th December, 12noon (week 11)	Michaelmas term mini-project submission deadline

Hilary Term

Monday 9th (week 0)	Provisional start date for invigilated examinations
Monday 16th January (week 1)	Hilary term lectures begin
Friday 27th January (week 2)	Examination entry for Hilary term courses with Hilary term submissions, all courses assessed by invigilated written examination in Trinity term and dissertation option
Monday 6th March (week 8)	Hilary term mini-projects released
Friday 10th March (week 8)	Hilary term lectures end
Monday 13th March, 12noon (week 9)	Hilary term take-home examinations released
Wednesday 15th March, 12noon (week 9)	Submission deadline for Hilary term take-home examinations
Tuesday 28th March, 12noon (week 11)	Hilary term mini-project submission deadline

Trinity Term

Monday 17th April (week 0)	Provisional start date for first set of Trinity term invigilated examinations
Monday 24th April (week 1)	Trinity term lectures begin
Friday 28th April (week 1)	Examination entry for Trinity term courses
Monday 22nd May, 12noon (week 5)	Dissertation submission deadline
Week 5	Oral presentations
Monday 29th May (week 6)	Provisional start date for second set of Trinity term invigilated examinations
Monday 29th May, 12noon (week 6)	Trinity term mini-projects released
Wednesday 14th – Tuesday 20th June (week 8/9)	Trinity term take-home examinations released between these dates.
Friday 16th June (week 8)	Trinity term lectures end
Friday 16th – Thursday 22nd June (week 8/9)	Submission deadlines for Trinity term take-home examinations between these dates
Monday 19th June, 12noon (week 9)	Trinity term mini-project submission deadline

B Course Synopses for 2016–17

Michaelmas Term

Quantum Field Theory — Dr Tomasz Lukowski — 24MT

Method of Assessment: Invigilated written examination in HT.
Weight: 1.5 units.
Areas: PT, CMT, Astro, foundational course.
Sequels: Advanced Quantum Field Theory for Particle Physics (HT), Conformal Field Theory (TT), Quantum Field Theory in Curved Space-Time (TT).

Summary: The course introduces concepts, methods and applications of quantum field theory. Special emphasis will be given to the quantum theory of scalar fields with quartic interaction in the path integral formalism.

Synopsis: Classical field theory, Noether's theorem, canonical quantization, path integral formulation of quantum mechanics, path integrals in field theory, generating functionals, finite temperature field theory, Wick theorem, Feynman diagrams, Feynman rules, divergences and regularisation, renormalisation, renormalisation group, Callan-Symanzik equation, beta-function, anomalous dimension, scattering theory and S-matrices, unitarity and analyticity of S-matrices, optical theorem.

Statistical Mechanics — Prof. Andrew Fowler — 16MT

Method of Assessment: Invigilated written examination in TT.
Weight: Unit.
Areas: CMT, Astro.
Remark: This course can be taken by students who have not studied this subject before (e.g., as Physics A1) but would like to be able to follow the more specialised courses offered in Hilary and Trinity that require familiarity with Statistical Mechanics.

Overview: Statistical mechanics is a subject which has fundamental and powerful connections with probability, mechanics, stochastic processes, fluid mechanics, thermodynamics, quantum mechanics (though we avoid this), and even philosophy. It is also notoriously inaccessible to applied mathematicians. This course will endeavour to trace a rational path towards classical statistical mechanics, beginning with classical mechanics, and then developing the concepts of thermodynamics through study of the Boltzmann equation. In passing, we derive the Navier-Stokes equations, before developing a mechanically-based formulation of thermodynamics and its famous second law concerning entropy. The latter parts of the course develop a variety of applications of current interest.

Learning Outcomes: Students will have developed a sound knowledge and appreciation of some of the tools, concepts, and computations used in the study of statistical mechanics. They will also get some exposure to some modern research topics in the field.

Synopsis: Classical mechanics: Newton's second law, D'Alembert's principle, Lagrange's equations, Hamilton's equations. Chaos. Probability: probability density functions, moment generating function, central limit theorem. Fluid mechanics: material derivative, Euler and Navier-Stokes equations, energy equation. Random walks, Brownian motion, diffusion equation. Loschmidt's paradox.

Liouville equation, BBGKY hierarchy, Boltzmann equation. The collision integral for a hard sphere gas. Boltzmann H theorem. Maxwellian distribution. Definition of entropy and temperature. Gibbs and Helmholtz free energies. Thermodynamic relations.

Classical statistical mechanics. Ergodic theorem, equiprobability. Microcanonical ensemble for the hard sphere gas, entropy. Canonical ensemble. Grand canonical ensemble.

Selected applications and extensions: for example, chemical potential, phase change, binary alloys, surface energy, radiative transfer, polymer solution theory, Arrhenius kinetics, nucleation theory, percolation theory, renormalisation.

Reading

1. David Chandler, *Introduction to Modern Statistical Mechanics* (Oxford University Press 1987)
2. M. Kardar, *Statistical Physics of Particles* (Cambridge University Press 2007)
3. F. Schwabl, *Statistical Mechanics* 2nd ed. (Springer-Verlag 2006)
4. J.P. Sethna, *Statistical Mechanics: Entropy, Order Parameters, and Complexity* (Oxford University Press 2006) [available online at http://pages.physics.cornell.edu/sethna/StatMech]

Advanced Quantum Theory: Path Integrals and Many-Particle Physics — Prof. Fabian Essler — 20MT

Method of Assessment: Invigilated written examination in TT.
Weight: 1.25 unit.
Areas: CMT, foundational course.
Sequel: Condensed Matter (HT).

Synopsis: Path integrals in Quantum Mechanics; the propagator. Path Integrals in Quantum Statistical Mechanics; correlation functions; perturbation theory; Feynman diagrams. Path Integrals and Transfer Matrices. Transfer matrix approach to the Ising Model. Second quantisation. Ideal Fermi gas in second quantization. Weakly interacting Bose gas: Bogoliubov theory; superfluidity. Spinwaves in a ferromagnet. Landau theory of phase transitions.

Nonequilibrium Statistical Physics — Prof. Ramin Golestanian — 4MT/20HT

Method of Assessment: Invigilated written examination in TT; homework completion requirement.
Weight: 1.5 unit.
Areas: CMT, Astro, foundational course.
Sequel: Soft Matter Physics (HT), Topics in Soft & Active Matter Physics (TT).

Synopsis: Part I. Stochastic Langevin dynamics. Brownian motion. Nonequilibrium kinetics. Master equation. Fokker-Planck equation. Kramers rate theory and first-passage time. Brownian ratchets. Fluctuation theorem.

Part II. Mean-field theory of reaction-diffusion processes. Pattern formation. Kuramoto model, synchronization transition. Stochastic field theory. Dynamical renormalization group.

Topological Quantum Theory: TQ Field Theories, TQ Matter, TQ Computation — Prof. Steve Simon — 16MT

Method of Assessment: No formal assessment; homework completion requirement.
Weight: Unit.

Areas: PT, CMT, Astro.

Synopsis:
Topological Quantum Field Theories
Particle statistics beyond bosons and fermions
Qubits and Toric Code
Discrete Gauge Theory
Structure of TQFT: Fusion, F and R
Topological Quantum Computation
Quantum Hall Effects
Berry Phases
Conformal Field Theory for Pedestrians
Topological Band Structures

Kinetic Theory — Dr Paul Dellar, Prof. Alex Schekochihin, Prof. James Binney — 24MT

Method of Assessment: Invigilated written examination in HT.
Weight: 1.5 units.
Areas: CMT, Astro, foundational course.
Sequel: Advanced Fluid Dynamics (HT), Collisionless Plasma Physics (HT), Collisional Plasma Physics(TT), Galactic and Planetary Dynamics (HT).

Synopsis: Part I (8 lectures). Kinetic theory of gases. Timescales and length scales. Hamiltonian mechanics of N particles. Liouville's Theorem. Reduced distributions. BBGKY hierarchy. Boltzmann-Grad limit and truncation of BBGKY equation for the 2-particle distribution assuming a short-range potential. Boltzmann collision operator. Its conservation properties. Boltzmanns entropy and the H-theorem. Maxwell-Boltzmann distribution. Linearised collision operator. Model collision operators: the BGK operator, Fokker-Planck operator. Derivation of hydrodynamics via Chapman-Enskog expansion. Viscosity and thermal conductivity.

Part II (9 lectures). Kinetic theory of plasmas. Kinetic description of a plasma: Debye shielding, micro- vs. macroscopic fields, Vlasov-Maxwell equations. Klimontovich's version of BBGKY (non-examinable). Plasma frequency. Partition of the dynamics into equilibrium and fluctuations. Linear theory: initial-value problem for the Vlasov-Poisson system, Laplace-tranform solution, the dielectric function, Landau prescription for calculating velocity integrals, Langmuir waves, Landau damping and kinetic instabilities (bump on tail), Weibel instability, sound waves, their damping, ion-acoustic instability, ion-Langmuir oscillations. Energy conservation. Heating. Entropy and free energy. Ballistic response and phase mixing. Role of collisions; coarse-graining. Quasilinear theory: general scheme. QLT for bump-on-tail instability in 1D.

Part III (7 lectures). Kinetic theory of self-gravitating systems. Mean-field models and their evolution exemplified by star clusters. Isothermal sphere, escape velocity, evaporation. Virial theorem, negative specific heat, gravothermal catastrophe. Heggie's theorem, binaries as a heat source. Angle-action coordinates, Jeans' theorem. Equation for slow evolution of mean-field distribution function: computation of cross correlations of fluctuating quantities (non-examinable). Enhanced diffusion along resonances. Application to stellar discs: particle dressing and swing amplification making Poisson noise anomalously large. Ultimate destabilisation of disc at collisionless level.

Radiative Processes and High Energy Astrophysics — Prof. Garret Cotter — 20MT

Method of Assessment: Take-home-exam examination in TT; homework completion requirement
Weight: 1.25 units.

Areas: Astro.

Synopsis: Radiative processes in astrophysics emission line formation and analysis; continuous and absorption line spectra; cosmic dust and extinction. Physics of interactions between high-energy particles and radiation (synchrotron, inverse-Compton, thermal bremsstrahlung). The interstellar and intergalactic medium. High-energy astrophysics accretion onto compact objects; the Eddington limit; black holes, active galaxies and relativistic jets. Acceleration of particles to ultra-high energies; cosmic ray and gamma ray astrophysics.

General Relativity I — Dr Andreas Braun — 16MT

Method of Assessment: Invigilated written examination in TT.
Weight: Unit.
Areas: PT, Astro, foundational course.
Remark: Some students may have studied this subject before (for example, as Physics B5).
Sequel: General Relativity II (HT), Cosmology (HT), Quantum Field Theory in Curved Space-Time (TT).

Overview: The course is intended as an elementary introduction to general relativity, the basic physical concepts of its observational implications, and the new insights that it provides into the nature of space time, and the structure of the universe. Familiarity with special relativity and electromagnetism will be assumed. The lectures will review Newtonian gravitation, tensor calculus and continuum physics in special relativity, physics in curved space time and the Einstein field equations. This will suffice for an account of simple applications to planetary motion, the bending of light and the existence of black holes.

Learning Outcomes: This course starts by asking how the theory of gravitation can be made consistent with the special-relativistic framework. Physical considerations (the principle of equivalence, general covariance) are used to motivate and illustrate the mathematical machinery of tensor calculus. The technical development is kept as elementary as possible, emphasising the use of local inertial frames. A similar elementary motivation is given for Einstein's equations and the Schwarzschild solution. Cosmological solutions are discussed. The learning outcomes are an understanding and appreciation of the ideas and concepts described above

Synopsis: Review of Newtonian gravitation theory and problems of constructing a relativistic generalisation. Review of Special Relativity. The equivalence principle. Tensor formulation of special relativity (including general particle motion, tensor form of Maxwell's equations and the energy momentum-tensor of dust). Curved space time. Local inertial coordinates. General coordinate transformations, elements of Riemannian geometry (including connections, curvature and geodesic deviation). Mathematical formulation of General Relativity, Einstein's equations (properties of the energy-momentum tensor will be needed in the case of dust only). Planetary motion, the bending of light, introduction to black hole solutions and the Schwarzschild solution. The introduction to cosmology including cosmological principles, homogeneity and isotropy, and the FriedmanRobertsonWalker solutions.

Reading

1. S. Carroll, *Space Time and Geometry: An Introduction to General Relativity* (Addison Welsey, 2003)
2. L.P. Hughston and K.P. Tod, *An Introduction to General Relativity,* LMS Student Text 5 (London Mathematical Society, Cambridge University Press, 1990), Chs 1–18.
3. N.M.J. Woodhouse, *Notes on Special Relativity*, Mathematical Institute Notes. Revised edition; published in a revised form as *Special Relativity, Lecture notes in Physics m6* (Springer-Verlag, 1992), Chs 1–7

Further Reading

1. B. Schutz, *A First Course in General Relativity* (Cambridge University Press, 1990).
2. R.M. Wald, *General Relativity* (Chicago, 1984).
3. W. Rindler, *Essential Relativity* (Springer-Verlag, 2nd edition, 1990).

Perturbation Methods — Prof. Jim Oliver — 16MT

Method of Assessment: Invigilated written examination in TT.
Weight: Unit.
Areas: PT, CMT, Astro, foundational course.
Sequel: Applied Complex Variables (HT).

Overview Perturbation methods underlie numerous applications of physical applied mathematics: including boundary layers in viscous flow, celestial mechanics, optics, shock waves, reaction-diffusion equations, and nonlinear oscillations. The aims of the course are to give a clear and systematic account of modern perturbation theory and to show how it can be applied to differential equations.

Synopsis Introduction to regular and singular perturbation theory: approximate roots of algebraic and transcendental equations. Asymptotic expansions and their properties. Asymptotic approximation of integrals, including Laplace's method, the method of stationary phase and the method of steepest descent. Matched asymptotic expansions and boundary layer theory. Multiple-scale perturbation theory. WKB theory and semiclassics.

Reading

1. E.J. Hinch, *Perturbation Methods* (Cambridge University Press, 1991), Chs. 1–3, 5–7.
2. C.M. Bender and S.A. Orszag, *Advanced Mathematical Methods for Scientists and Engineers* (Springer, 1999), Chs. 6, 7, 9–11.
3. J. Kevorkian and J.D. Cole, *Perturbation Methods in Applied Mathematics* (Springer-Verlag, 1981), Chs. 1, 2.1–2.5, 3.1, 3.2, 3.6, 4.1, 5.2.

Numerical Linear Algebra — Prof. Andy Wathen — 16MT

Method of Assessment: Invigilated written examination in TT.
Weight: Unit.
Areas: PT, CMT, Astro.

Overview: Linear Algebra is a central and widely applicable part of mathematics. It is estimated that many (if not most) computers in the world are computing with matrix algorithms at any moment in time whether these be embedded in visualization software in a computer game or calculating prices for some financial option. This course builds on elementary linear algebra and in it we derive, describe and analyse a number of widely used constructive methods (algorithms) for various problems involving matrices.

Numerical Methods for solving linear systems of equations, computing eigenvalues and singular values and various related problems involving matrices are the main focus of this course.

Synopsis: Common problems in linear algebra. Matrix structure, singular value decomposition. QR factorization, the QR algorithm for eigenvalues. Direct solution methods for linear systems, Gaussian elimination and its variants. Iterative solution methods for linear systems.

Chebyshev polynomials and Chebyshev semi-iterative methods, conjugate gradients, convergence analysis, preconditioning.

Reading
L. N. Trefethen and D. Bau III, *Numerical Linear Algebra* (SIAM, 1997).

J. W. Demmel, *Applied Numerical Linear Algebra* (SIAM, 1997).

A. Greenbaum, *Iterative Methods for Solving Linear Systems* (SIAM, 1997).

G. H. Golub and C. F. van Loan, *Matrix Computations* (John Hopkins University Press, 3rd edition, 1996).

H. C. Elman, D. J. Silvester and A. J. Wathen, *Finite Elements and Fast Iterative Solvers* (Oxford University Press, 1995), only chapter 2.

Groups and Representations — Prof. Andre Lukas — 24MT

Method of Assessment: Invigilated written examination in HT; homework completion requirement.
Weight: 1.5 Unit.
Areas: PT, CMT, Astro.

Synopsis: Basics on groups, representations, Schur's Lemma, representations of finite groups, Lie groups, Lie algebras, Lorentz and Poincare groups, SU(n), SO(n), spinor representations, roots, classification of simple Lie algebras, weights, representations and Dynkin formalism.

Algebraic Topology — Prof. Christopher Douglas — 16MT

Method of Assessment: Invigilated written examination in TT.
Weight: Unit.
Areas: PT.

Overview: Homology theory is a subject that pervades much of modern mathematics. Its basic ideas are used in nearly every branch, pure and applied. In this course, the homology groups of topological spaces are studied. These powerful invariants have many attractive applications. For example we will prove that the dimension of a vector space is a topological invariant and the fact that 'a hairy ball cannot be combed'.

Learning Outcomes: At the end of the course, students are expected to understand the basic algebraic and geometric ideas that underpin homology and cohomology theory. These include the cup product and Poincaré Duality for manifolds. They should be able to choose between the different homology theories and to use calculational tools such as the Mayer-Vietoris sequence to compute the homology and cohomology of simple examples, including projective spaces, surfaces, certain simplicial spaces and cell complexes. At the end of the course, students should also have developed a sense of how the ideas of homology and cohomology may be applied to problems from other branches of mathematics.

Synopsis: Chain complexes of free Abelian groups and their homology. Short exact sequences. Delta complexes and their homology. Euler characteristic.

Singular homology of topological spaces. Relative homology and the Five Lemma. Homotopy invariance and excision (details of proofs not examinable). Mayer-Vietoris Sequence. Equivalence of simplicial and singular homology.

Degree of a self-map of a sphere. Cell complexes and cellular homology. Application: the hairy ball theorem.

Cohomology of spaces and the Universal Coefficient Theorem (proof not examinable). Cup products. Künneth Theorem (without proof). Topological manifolds and orientability. The fundamental class of an orientable, closed manifold and the degree of a map between manifolds of the same dimension. Poincaré Duality (without proof).

Reading

1. A. Hatcher, *Algebraic Topology* (Cambridge University Press, 2001). Chapters 2 and 3.
2. G. Bredon, *Topology and Geometry* (Springer, 1997). Chapters 4 and 5.
3. J. Vick, *Homology Theory,* Graduate Texts in Mathematics 145 (Springer, 1973).

Algebraic Geometry — Prof. Alexander Ritter — 16MT

Method of Assessment: Invigilated written examination in TT.
Weight: Unit.
Areas: PT.

Overview: Algebraic geometry is the study of algebraic varieties: an algebraic variety is roughly speaking, a locus defined by polynomial equations. One of the advantages of algebraic geometry is that it is purely algebraically defined and applied to any field, including fields of finite characteristic. It is geometry based on algebra rather than calculus, but over the real or complex numbers it provides a rich source of examples and inspiration to other areas of geometry.

Synopsis: Affine algebraic varieties, the Zariski topology, morphisms of affine varieties. Irreducible varieties.

Projective space. Projective varieties, affine cones over projective varieties. The Zariski topology on projective varieties. The projective closure of affine variety. Morphisms of projective varieties. Projective equivalence.

Veronese morphism: definition, examples. Veronese morphisms are isomorphisms onto their image; statement, and proof in simple cases. Subvarieties of Veronese varieties. Segre maps and products of varieties, Categorical products: the image of Segre map gives the categorical product.

Coordinate rings. Hilbert's Nullstellensatz. Correspondence between affine varieties (and morphisms between them) and finitely generate reduced k-algebras (and morphisms between them). Graded rings and homogeneous ideals. Homogeneous coordinate rings.

Categorical quotients of affine varieties by certain group actions. The maximal spectrum.

Primary decomposition of ideals.

Discrete invariants projective varieties: degree dimension, Hilbert function. Statement of theorem defining Hilbert polynomial.

Quasi-projective varieties, and morphisms of them. The Zariski topology has a basis of affine open subsets. Rings of regular functions on open subsets and points of quasi-projective varieties. The ring of regular functions on an affine variety in the coordinate ring. Localisation and relationship with rings of regular functions.

Tangent space and smooth points. The singular locus is a closed subvariety. Algebraic re-formulation of the tangent space. Differentiable maps between tangent spaces.

Function fields of irreducible quasi-projective varieties. Rational maps between irreducible varieties, and composition of rational maps. Birational equivalence. Correspondence between dominant rational maps and homomorphisms of function fields. Blow-ups: of affine space at appoint, of subvarieties of affine space, and general quasi-projective varieties along general subvarieties. Statement of Hironaka's Desingularisation Theorem. Every irreducible variety is birational to hypersurface. Re-formulation of dimension. Smooth points are a dense open subset.

Reading
KE Smith et al, *An Invitation to Algebraic Geometry*, (Springer 2000), Chapters 1–8.

Further Reading

1. M Reid, *Undergraduate Algebraic Geometry*, LMS Student Texts 12, (Cambridge 1988).
2. K Hulek, *Elementary Algebraic Geometry*, Student Mathematical Library 20. (American Mathematical Society, 2003).
3. A Gathmann, *Algebraic Geometry lecture notes*, online: **www.mathematik.uni-kl.de/en/agag/members/professors/gathmann/notes/alggeom**
4. I Shafarevich, *Basic Algebraic Geometry 1*, (Springer, 1994).
5. D Mumford, *The Red Book of Varieties and Schemes*, (Springer, 2009).

Differential Geometry — Prof. Dominic Joyce — 16MT

Method of Assessment: Invigilated written examination in TT.
Weight: Unit.
Areas: PT, Astro.

Overview: A manifold is a space such that small pieces of it look like small pieces of Euclidean space. Thus a smooth surface is an example of a (2-dimensional) manifold.

Manifolds are the natural setting for parts of classical applied mathematics such as mechanics, as well as general relativity. They are also central to areas of pure mathematics such as topology and certain aspects of analysis.

In this course we introduce the tools needed to do analysis on manifolds. We prove a very general form of Stokes' Theorem which includes as special cases the classical theorems of Gauss, Green and Stokes. We also introduce the theory of de Rham cohomology, which is central to many arguments in topology.

Learning Outcomes: The candidate will be able to manipulate with ease the basic operations on tangent vectors, differential forms and tensors both in a local coordinate description and a global coordinate-free one; have a knowledge of the basic theorems of de Rham cohomology and some simple examples of their use; know what a Riemannian manifold is and what geodesics are.

Synopsis: Smooth manifolds and smooth maps. Tangent vectors, the tangent bundle, induced maps. Vector fields and flows, the Lie bracket and Lie derivative.

Exterior algebra, differential forms, exterior derivative, Cartan formula in terms of Lie derivative. Orientability. Partitions of unity, integration on oriented manifolds.

Stokes' theorem. De Rham chomology. Applications of de Rham theory including degree.

Riemannian metrics. Isometries. Geodesics.

Reading

1. M. Spivak, *Calculus on Manifolds*, (W. A. Benjamin, 1965).

2. M. Spivak, *A Comprehensive Introduction to Differential Geometry*, Vol. 1, (1970).
3. W. Boothby, *An Introduction to Differentiable Manifolds and Riemannian Geometry*, 2nd edition, (Academic Press, 1986).
4. M. Berger and B. Gostiaux, *Differential Geometry: Manifolds, Curves and Surfaces.* Translated from the French by S. Levy, (Springer Graduate Texts in Mathematics, 115, Springer–Verlag (1988)) Chapters 0–3, 5–7.
5. F. Warner, *Foundations of Differentiable Manifolds and Lie Groups*, (Springer Graduate Texts in Mathematics, 1994).
6. D. Barden and C. Thomas, *An Introduction to Differential Manifolds.* (Imperial College Press, London, 2003.)

Viscous Flow — Prof. Sarah Waters — 16 MT

Remark: This course will not be offered as part of the Mathematical and Theoretical Physics programme in 2016–17. However, students may opt to take it as an optional background course, particularly those who have not studied basic Fluid Dynamics (e.g., as Physics B1) and would like to be able to follow the more specialised courses offered in Hilary and Trinity and requiring familiarity with this subject. The course would not count towards a student's 10 units. Students wishing to take Viscous Flow should discuss this with the course director or their advisor. For further information about the course please see **http://www0.maths.ox.ac.uk/courses/course/28736/synopsis**.

Hilary Term

Advanced Fluid Dynamics — Prof. Alexander Schekochihin, Dr Paul Dellar — 16HT

Method of Assessment: Invigilated written examination in TT.
Weight: Unit.
Areas: CMT, Astro.
Prequels: Kinetic Theory (MT), an undergraduate course on Fluid Dynamics.
Prerequisites: basic familiarity with fluid equations and stress tensors as provided, e.g., by Kinetic Theory (MT). **Sequels**: Collisional Plasma Physics (TT), Soft Matter (HT).

Syllabus: Part I. Magnetohydrodynamics (10 lectures) MHD equations: conservation laws in a conducting fluid; Maxwell stress/magnetic forces; induction equation; Lundquist theorem, flux freezing, amplification of magnetic field. MHD in a strong guide field: MHD waves; high-beta and anisotropic limits and orderings; incompressible MHD, Elsasser MHD, Reduced MHD. Static MHD equilibria, force-free solutions, helicity, Taylor relaxation. Energy principle. Instabilities: interchange, Z-pinch. Part II. Complex fluids (6 lectures) Fluid mechanics with general extra stress. Dilute suspension of spheres: Einstein viscosity. Dilute suspension of beads on springs: Oldroyd-B model for polymeric liquids, elastic waves, anisotropic pressure. Dilute suspension of orientable particles (ellipsoids): road map to liquid crystals, swimmers and active matter.

Soft Matter Physics — Prof. Julia Yeomans, Prof. Ard Louis — 16HT

Method of Assessment: No formal assessment; homework completion requirement.
Weight: Unit.
Areas: CMT, Astro.

Prequel/pre-requisite: Nonequilibrium Statistical Physics (MT)
Sequel: Topics in Soft and Active Matter Physics (TT).

Syllabus: Polymers: statics and dynamics. Membranes. Liquid Crystals and topological defects. Colloids: dispersion interactions and transport. Diffusion-reaction processes and pattern formation. Self-assembly.

Advanced Quantum Field Theory for Particle Physics — Prof. Graham Ross — 24HT

Method of Assessment: Invigilated written examination in TT.
Weight: 1.5 units.
Areas: PT.
Prequel/pre-requisite: Quantum Field Theory (MT)
Sequels: The Standard Model (TT), Beyond the Standard Model (TT), Non-perturbative Methods in Quantum Field Theory (TT)

Syllabus: Quantum Electrodynamics: Introduction, photon propagator, scalar electrodynamics (Feynman rules, radiative corrections), canonical quantization, fermions (fermions propagator, path integral and Feynman rules), spinor electrodynamics, sample calculations (scattering in spinor electrodynamics), beta function in QED. Non-Abelian Quantum Field Theory: SU(N) local gauge theory, path integral, gauge fixing, BRST, spontaneous symmetry breaking, anomalies, introduction to the standard model.

Quantum Matter: Superconductors, Superfluids, and Fermi Liquids — Prof. Steve Simon — 16HT

Method of Assessment: Invigilated written exam in TT; homework completion requirement.
Weight: 1 unit.
Areas: CMT.
Prequel/pre-requisite: Advanced Quantum Theory.
Sequels: Topics in Quantum Condensed Matter Physics (TT).

Syllabus: Intro to Superfluids and Superconductors
Two Fluid Model and Vortices
Landau Criterion and Intro to Charged Superfluids / London Theory
Superconducting Vortices / Type I and Type II Superconductors
Microscopic Theory / Second Quantization / Gross Pitaevskii and Bogoliubov Theory
Feynman Theory of Superfluidity
Ginzburg Landau Theory / Anderson Higgs Mechanism / Coherence Length / Vortex Structure
Interacting Fermions / Second Quantization / First Order Perturbation Theory / Hartree and Fock Terms
Hartree Fock Theory
Coulomb Interaction / Screening and Response
Linear Response Theory / Lindhard, Thomas Fermi, RPA / Plasmons
Landau Theory of Fermi Liquids part 1
Landau Theory of Fermi Liquids part 2
BCS theory part 1: Phonon Attraction Mechanism / Cooper Problem
BCS wavefunction
Bogoliubov Excitation Spectrum
plus if time permits
Quantum Hall Effect / Laughlin Gauge Invariance Argument
Chern Numbers / Quantum Spin Hall / Topological Insulators in 2 and 3 D
Fractional Quantum Hall Effect

String Theory I — Prof. Philip Candelas — 16HT

Method of Assessment: Mini-project.
Weight: Unit.
Areas: PT.
Pre-requisite: Quantum Field Theory (MT)
Sequels: String Theory II (TT), Introduction to Gauge-String Duality (TT)

Syllabus: String actions, equations of motion and constraints, open and closed strings — boundary conditions, Virasoro algebra, ghosts and BRS, physical spectrum, elementary consideration of D branes, Veneziano amplitude.

Networks — Dr Heather Harrington — 16HT

Method of Assessment: Mini-project.
Weight: Unit.
Areas: CMT.
Pre-requisite: Maths C5.3 Statistical Mechanics or another undergraduate course in Statistical Mechanics.
Sequel: Complex Systems (TT).

Overview: This course aims to provide an introduction to network science, which can be used to study complex systems of interacting agents. Networks are interesting both mathematically and computationally, and they are pervasive in physics, biology, sociology, information science, and myriad other fields. The study of networks is one of the "rising stars" of scientific endeavors, and networks have become among the most important subjects for applied mathematicians to study. Most of the topics to be considered are active modern research areas.

Learning Outcomes: Students will have developed a sound knowledge and appreciation of some of the tools, concepts, models, and computations used in the study of networks. The study of networks is predominantly a modern subject, so the students will also be expected to develop the ability to read and understand current (2016) research papers in the field.

Synopsis:

1. Introduction and Basic Concepts (1-2 lectures): nodes, edges, adjacencies, weighted networks, unweighted networks, degree and strength, degree distribution, other types of networks.

2. Small Worlds (2 lectures): clustering coefficients, paths and geodesic paths, Watts-Strogatz networks [focus is on modelling and heuristic calculations].

3. Toy Models of Network Formation (2 lectures): preferential attachment, generalizations of preferential attachment, network optimization.

4. Additional Summary Statistics and Other Useful Concepts (2 lectures): modularity and assortativity, degree-degree correlations, centrality measures, communicability, reciprocity and structural balance.

5. Random Graphs (2 lectures): Erdős-Rényi graphs, configuration model, random graphs with clustering, other models of random graphs or hypergraphs; application of generating-function methods [focus is on modelling and heuristic calculations; material in this section forms an important basis for sections 6 and 7].

6. Community Structure and Mesoscopic Structure (2 lectures): linkage clustering, optimization of modularity and other quality functions, overlapping communities, other methods and generalizations.

7. Dynamics on (and of) Networks (3-4 lectures): general ideas, models of biological and social contagions, percolation, voter and opinion models, temporal networks, other topics.

8. Additional Topics (0-2 lectures): games on networks, exponential random graphs, network inference, other topics of special interest to students [depending on how much room there is and interest of current students].

Reading
(most important are [2] and [3]):

1. A. Barrat et al, *Dynamical Processes on Complex Networks*, Cambridge University Press, 2008
2. M. E. J. Newman, *Networks: An Introduction*, Oxford University Press, 2010
3. Various papers and review articles (see the Math C5.4 blog at http://networksoxford.blogspot.co.uk for examples). The instructor will indicate a small number of specific review articles that are required reading, and other helpful (but optional) articles will also be indicated.

Collisionless Plasma Physics — Prof. Felix Parra-Diaz — 16HT

Method of Assessment: Take-home examination.
Weight: Unit.
Areas: Astro.
Prequel: Kinetic Theory (MT), an undergraduate course on Electricity and Magnetism.
Sequel: Collisional Plasma Physics (TT) (note however that this course is self-contained and can be taken without continuing to Collisional Plasma Physics).

Syllabus: Part I. Magnetized plasmas (8 lectures). Particle motion. Drift kinetics. Drift waves and slab Ion Temperature Gradient instability. Barnes damping of compressional Alfven waves. Part II. Plasma waves (8 lectures). Cold plasma waves in a magnetized plasma. WKB theory of cold plasma wave propagation in an inhomogeneous plasma, cut-offs and resonances. Hot plasma waves in a magnetized plasma. Cyclotron resonance.

Supersymmetry and Supergravity — Dr Sven Krippendorf — 24HT

Method of Assessment: Invigilated written examination in TT.
Weight: 1.5 units.
Areas: PT.
Pre-requisite: Quantum Field Theory (MT)

Syllabus: Motivations for supersymmetry, spinor algebras and representations, supersymmetry algebra and representations, extended supersymmetry and BPS states, superfields, SUSY field theories, non-renormalisation theorems, SUSY breaking, the MSSM and its phenomenology, rescaling anomalies, NSVZ beta function, basic properties of supergravity, SUSY in higher dimensions.

Galactic and Planetary Dynamics ("Celestial Mechanics for the 21st Century") — Dr John Magorrian — 16HT

Method of Assessment: Mini-project.
Weight: Unit.

Areas: Astro.
Prequel/pre-requisite: Kinetic Theory (MT).

Syllabus: Review of Hamiltonian mechanics. Orbit integration. Classification of orbits and integrability. Construction of angle-action variables. Hamiltonian perturbation theory. Simple examples of its application to the evolution of planetary and stellar orbits. Methods for constructing equilibrium galaxy models. Applications. Fundamentals of N-body simulation. Dynamical evolution of isolated galaxies. Interactions with companions.

Geophysical Fluid Dynamics — Dr Andrew Wells — 16HT

Method of Assessment: Invigilated written examination in TT.
Weight: Unit.
Areas: Astro.
Prequel: an introductory course on Fluid Dynamics.

Syllabus: Rotating frames of reference, vorticity equation, Ertels theorem, Rossby number, Ekman number, Taylor-Proudman theorem. Geostrophic and hydrostatic balance, thermal wind relation, pressure coordinates, f and beta-planes. Shallow water and reduced gravity models, conservation laws for energy and potential vorticity, flow over topography, inertia-gravity waves, equations for nearly geostrophic motion, Rossby waves, Kelvin waves. Linearised equations for a stratified, incompressible fluid, internal gravity waves, vertical modes. Planetary Geostrophy. Quasigeostrophic approximation: quasigeostrophic potential vorticity equation and Rossby wave solutions, vertical propagation and trapping. Barotropic and baroclinic instability, necessary conditions for instability of zonal flow, Eady model of baroclinic instability. Wave-mean flow interaction, transformed Eulerian mean, Eliassen-Palm flux, non-acceleration theorem. Ekman layers and upwelling. Sverdrup balance and ocean gyres, western intensification, simple models for the vertical structure of ocean circulation and meridional overturning circulation. Angular momentum and Held-Hou model of Hadley circulations. Applications to atmospheric flow on Mars and gas giant planets.

Astrophysical Gas Dynamics — Prof. Philipp Podsiadlowski and Prof. Caroline Terquem — 10HT/10TT

Method of Assessment: Take-home-exam in TT; homework completion requirement.
Weight: 1.25 units.
Areas: Astro.

Syllabus:
Part 1: Astrophysical Gas Dynamics (Prof Terquem, 10 lectures HT)
Principles of hydrodynamics. Equilibrium and stability of fluid systems under gravity. Waves. Shocks. Viscous flows. Applications: star formation, blast waves, winds, accretion discs

Part 2: Disc Accretion in Astrophysics: Theory and Applications (Prof Podsiadlowski, 10 lectures in the 1st half of Trinity Term 2017)
Thin discs (the alpha disc model, disc structure and their appearance), the thermal/viscous instability, resonances; thick discs (including radiation-pressure dominated discs), self-gravitating discs and their stability (including the Toomre criterion); relativistic disc accretion, optically thin advection-dominated flows, super-Eddington accretion, the source of disc viscosity (including the magneto-rotational instability), mass loss and jets from accretion discs. The course will emphasize a wide range of applications of accretion-disc theory, such as compact binaries, including black-hole binaries, ultraluminous X-ray sources, X-ray pulsars, proto-stellar systems, gamma-ray bursts.

Introduction to Quantum Information — Prof. Artur Ekert — 16HT

Method of Assessment: Invigilated, written examination in TT.
Weight: Unit.
Areas: PT/CMT/Astro.
Prequel/Pre-requisite: The course material should be of interest to physicists, mathematicians, computer scientists, and engineers. The following will be assumed as prerequisites for this course:

- elementary probability, complex numbers, vectors and matrices;
- Dirac bra-ket notation;
- a basic knowledge of quantum mechanics especially in the simple context of finite dimensional state spaces (state vectors, composite systems, unitary matrices, Born rule for quantum measurements);
- basic ideas of classical theoretical computer science (complexity theory) would be helpful but are not essential.

Prerequisite notes will be provided giving an account of the necessary material. It would be desirable for you to look through these notes slightly before the start of the course.

Overview

The classical theory of computation usually does not refer to physics. Pioneers such as Turing, Church, Post and Goedel managed to capture the correct classical theory by intuition alone and, as a result, it is often falsely assumed that its foundations are self-evident and purely abstract. They are not! Computers are physical objects and computation is a physical process. Hence when we improve our knowledge about physical reality, we may also gain new means of improving our knowledge of computation. From this perspective it should not be very surprising that the discovery of quantum mechanics has changed our understanding of the nature of computation. In this series of lectures you will learn how inherently quantum phenomena, such as quantum interference and quantum entanglement, can make information processing more efficient and more secure, even in the presence of noise.

Synopsis

1. Bits, gates, networks, Boolean functions, reversible and probabilistic computation
2. “Impossible” logic gates, amplitudes, quantum interference
3. One, two and many qubits
4. Entanglement and entangling gates
5. From interference to quantum algorithms
6. Algorithms, computational complexity and Quantum Fourier Transform
7. Phase estimation and quantum factoring
8. Non-local correlations and cryptography
9. Bell’s inequalities
10. Density matrices and CP maps
11. Decoherence and quantum error correction

Reading Beyond the Quantum Horizon by D. Deutsch and A. Ekert, Scientific American, Sep 2012.

Less reality more security by A. Ekert, Physics World, Sep 2009.

The Limits of Quantum Computers, by S. Aaronson, Scientific American, Mar 2008.

A Do-It-Yourself Quantum Eraser by R. Hillmer and P. Kwiat, Scientific American, May 2007.

Quantum Seeing in the Dark by P. Kwiat et al, Scientific American, Nov 1996

Physical Limits of Computation by C.H. Bennett and R. Landauer, Scientific American, Jul 1985.

General Relativity II — Prof. Xenia de la Ossa — 16HT

Method of Assessment: Invigilated written examination in TT.
Weight: Unit.
Areas: PT, Astro.
Prequel/Pre-requisite: General Relativity I (MT) or equivalent.

Overview: In this, the second course in General Relativity, we have two principal aims. We first aim to increase our mathematical understanding of the theory of relativity and our technical ability to solve problems in it. We apply the theory to a wider class of physical situations, including gravitational waves and black hole solutions. Orbits in the Schwarzschild solution are given a unified treatment which allows a simple account of the three classical tests of Einstein's theory. This leads to a greater understanding of the Schwarzschild solution and an introduction to its rotating counterpart, the Kerr solution. We analyse the extensions of the Schwarzschild solution show how the theory of black holes emerges and exposes the radical consequences of Einstein's theory for space-time structure.

Synopsis: Mathematical background, the Lie derivative and isometries. The Einstein field equations with matter; the energy-momentum tensor for a perfect fluid; equations of motion from the conservation law. Linearised general relativity and the metric of an isolated body. Motion on a weak gravitational field and gravitational waves. The Schwarzschild solution and its extensions; Eddington-Finkelstein coordinates and the Kruskal extension. Penrose diagrams and the area theorem. Stationary, axisymmetric metrics and orthogonal transitivity; the Kerr solution and its properties; interpretation as rotating black hole.

Reading

1. S. Carroll, *Space Time and Geometry: An Introduction to General Relativity* (Addison Welsey, 2003)
2. L. P. Hughston and K. P. Tod, *An Introduction to General Relativity*, LMS Student Text 5, CUP (1990), Chs.19, 20, 22-26.
3. R. M. Wald, *General Relativity*, Univ of Chicago Press (1984).

Further Reading

1. B. Schutz, *A First Course in General Relativity* (Cambridge University Press, 1990).
2. R.M. Wald, *General Relativity* (Chicago, 1984).
3. W. Rindler, *Essential Relativity* (Springer-Verlag, 2nd edition, 1990).
4. S. Hawking and G. Ellis, *The Large Scale of the Universe*, (Cambridge Monographs on Mathematical Physics, 1973).

Cosmology — Prof. Pedro Ferreira — 16HT

Method of Assessment: No formal assessment; homework completion requirement.
Weight: Unit.
Areas: Astro, PT.
Pre-requisite: General Relativity I (MT) or equivalent.

Syllabus: Einstein field equations and the Friedman equations, universe models, statistics of expanding background, relativistic cosmological perturbations, observations, from the Hubble flow to the CMB.

Non-perturbative Methods in Quantum Field Theory — Prof. Mike Teper —- 8HT/8TT

Method of Assessment: No formal assessment; homework completion requirement.
Weight: Unit.
Areas: PT, CMT.
Prequel/pre-requisite: Advanced Quantum Field Theory for Particle Physics (HT).

Syllabus

Lattice Field Theory (HT). Motivation; Euclidean Path Integral and Stat Mech partition functions; transfer matrix and Hamiltonian; spin models; gauge fields on a lattice and continuum limit(s); strong coupling calculations; Wilson loops and confinement; Markovian Monte Carlo: Metropolis, heat bath. Fermions on a lattice. Some applications drawn from: the mass spectrum; the running coupling; large N; non-zero temperature; (near-)conformal field theories; topology on the lattice.

Solitons (TT). Kinks in D=1+1 scalar Field Theory. A no-go theorem and its limitations: vortices in D=2+1 scalar FT (KT phase transition) and in D=2+1 gauge+scalar FT; solitonic 'strings' in D=3+1 gauge+scalar FT (Meissner effect and dual-superconductor confinement); textures; domain walls; homotopy groups. Monopoles in the D=3+1 Georgi-Glashow model.

Instantons (TT). Tunnelling in D=1+1 Quantum Mechanics. Abelian-Higgs model in D=1+1 FT: the dilute gas approximation, n-vacua and theta-vacua; Wilson loops and linear confinement. SU(2) gauge fields in D=3+1: the dilute gas calculation, n-vacua (Chern-Simons) and theta-vacua, SU(N) and intertwined theta-vacua. Fermions and index theorems; anomalies and chiral symmetry breaking (Banks-Casher).

Applied Complex Variables — Prof. Peter Howell — 16HT

Method of Assessment: Invigilated written examination in TT.
Weight: Unit.
Areas: PT, CMT, Astro.
Prequel: Perturbation Methods (MT).

Overview: The course begins where core second-year complex analysis leaves off, and is devoted to extensions and applications of that material. The solution of Laplace's equation using conformal mapping techniques is extended to general polygonal domains and to free boundary problems. The properties of Cauchy integrals are analysed and applied to mixed boundary value problems and singular integral equations. The Fourier transform is generalised to complex values of the transform variable, and used to solve mixed boundary value problems and integral equations via the Wiener-Hopf method.

Synopsis: Review of core complex analysis, analytic continuation, multifunctions, contour integration, conformal mapping and Fourier transforms.

Riemann mapping theorem (in statement only). Schwarz-Christoffel formula. Solution of Laplace's equation by conformal mapping onto a canonical domain; applications including inviscid hydrodynamics; Free streamline flows in the hodograph plane. Unsteady flow with free boundaries in porous media.

Application of Cauchy integrals and Plemelj formulae. Solution of mixed boundary value problems motivated by thin aerofoil theory and the theory of cracks in elastic solids. Reimann-Hilbert problems. Cauchy singular integral equations. Complex Fourier transform. Contour integral solutions of ODE's. Wiener-Hopf method.

Reading

1. G. F. Carrier, M. Krook and C.E. Pearson, *Functions of a Complex Variable*(Society for Industrial and Applied Mathematics, 2005.) ISBN 0898715954.
2. M. J. Ablowitz and A. S. Fokas, *Complex Variables: Introduction and Applications* (2nd edition, Cambridge University Press, 2003). ISBN 0521534291.
3. J. R. Ockendon, S. D. Howison, A. A. Lacey and A. B. Movichan, *Applied Partial Differential Equations: Revised Edition* (Oxford University Press, 2003). ISBN 0198527713. Pages 195–212.

Geometric Group Theory — Prof. Panos Papazoglou — 16HT

Method of Assessment: Invigilated written examination in TT.
Weight: Unit.
Areas: PT.

Overview: The aim of this course is to introduce the fundamental methods and problems of geometric group theory and discuss their relationship to topology and geometry.

The first part of the course begins with an introduction to presentations and the list of problems of M. Dehn. It continues with the theory of group actions on trees and the structural study of fundamental groups of graphs of groups.

The second part of the course focuses on modern geometric techniques and it provides an introduction to the theory of Gromov hyperbolic groups.

Synopsis: Free groups. Group presentations. Dehn's problems. Residually finite groups.

Group actions on trees. Amalgams, HNN-extensions, graphs of groups, subgroup theorems for groups acting on trees.

Quasi-isometries. Hyperbolic groups. Solution of the word and conjugacy problem for hyperbolic groups.

If time allows: Small Cancellation Groups, Stallings Theorem, Boundaries.

Reading.

1. J.P. Serre, *Trees* (Springer Verlag 1978).
2. M. Bridson, A. Haefliger, *Metric Spaces of Non-positive Curvature, Part III* (Springer, 1999), Chapters I.8, III.H.1, III. *Gamma* 5.
3. H. Short *et al.*, 'Notes on word hyperbolic groups', *Group Theory from a Geometrical Viewpoint, Proc. ICTP Trieste* (eds E. Ghys, A. Haefliger, A. Verjovsky, World Scientific 1990)

   available online at: http://www.cmi.univ-mrs.fr/ hamish/
4. C.F. Miller, *Combinatorial Group Theory*, notes:
   http://www.ms.unimelb.edu.au/ cfm/notes/cgt-notes.pdf.

Further Reading.

1. G. Baumslag, *Topics in Combinatorial Group Theory* (Birkhauser, 1993).
2. O. Bogopolski, *Introduction to Group Theory* (EMS Textbooks in Mathematics, 2008).
3. R. Lyndon, P. Schupp, *Combinatorial Group Theory* (Springer, 2001).
4. W. Magnus, A. Karass, D. Solitar,*Combinatorial Group Theory: Presentations of Groups in Terms of Generators and Relations* (Dover Publications, 2004).
5. P. de la Harpe, *Topics in Geometric Group Theory*, (University of Chicago Press, 2000).

Waves and Compressible Flow — Prof. Ian Hewitt — 16HT

Remark: This course will not be offered as part of the Mathematical and Theoretical Physics programme in 2016–17. However, students may opt to take it as an optional background course, though the course would not count towards a student's 10 units. Students wishing to take Waves and Compressible Flow should discuss this with the course director or their advisor. For further information about the course please see **http://www0.maths.ox.ac.uk/courses/course/28737/synopsis**.

Nonlinear Systems — Prof. Alain Goriely — 16HT

Remark: This course will not be offered as part of the Mathematical and Theoretical Physics programme in 2016–17. However, students may opt to take it as an optional background course, though the course would not count towards a student's 10 units. Students wishing to take Nonlinear Systems should discuss this with the course director or their advisor. For further information about the course please see **http://www0.maths.ox.ac.uk/courses/course/28740/synopsis**.

Trinity Term

Conformal Field Theory — Prof. Fernando Alday — 16TT

Method of Assessment: No formal assessment; homework completion requirement.
Weight: Unit.
Areas: PT, CMT.
Prequel/pre-requisite: Quantum Field Theory (MT)

Syllabus: Scale invariance and conformal invariance in critical behaviour, the role of the stress tensor, radial quantisation and the Virasoro algebra, CFT on the cylinder and torus, height models, loop models and Coulomb gas methods, boundary CFT and Schramm-Loewner evolution, perturbed conformal field theories: Zamolodchikov's c-theorem, integrable perturbed CFTs: S-matrices and form factors.

Introduction to Gauge-String Duality — Prof. Andrei Starinets — 16TT

Method of Assessment: No formal assessment; homework completion requirement.
Weight: Unit.
Areas: PT.
Pre-requisite: Quantum Field Theory (MT).

Syllabus: Duality in lattice statistical mechanics and quantum filed theory (an overview), black hole thermodynamics and black hole entropy, D-branes, the AdS-CFT correspondence, main recipes of gauge-string duality, gauge-string duality at finite temperature and density, fluid mechanics, black holes and holography, transport in strongly correlated systems from dual gravity, gauge-string duality and condensed matter physics, modern developments.

Topics in Soft and Active Matter Physics — Prof. Julia Yeomans — 8TT

Method of Assessment: No formal assessment; homework completion requirement.
Weight: 0.5 unit.
Areas: CMT
Prequels: Soft Matter Physics (HT), Advanced Fluid Dynamics (HT).
Pre-requisites: Soft Matter Physics (HT).

Syllabus: This is a reading course. Under the guidance of the course organiser, students will give presentations based on key papers in soft condensed matter theory. Some examples of the topics for these presentations are: Active nematics and active gels. Wetting, spreading and contact line dynamics. Hydrodynamics of microswimmers: Stokes equation, scallop theorem, multipole expansion, active suspensions. Fluctuations and response.

Complex Systems — T.B.C. — 16TT

Please note that it has not yet been confirmed that this course will be offered in 2016-17.
Method of Assessment: Mini-project.
Weight: Unit.
Areas: CMT, Astro.
Prequel: Networks (HT).
Pre-requisite: Statistical Mechanics (MT) or another undergraduate course in statistical mechanics.

Syllabus: Percolation, fractals, self-organised criticality, and power laws. Stochastics and generative models: random walks, preferential attachment, master equations. Dynamical systems on networks: includes models of epidemics, social influence, voter models, etc. and how they are affected by network architecture. Agent-based models. Numerical methods: Monte Carlo, simulated annealing, etc.

String Theory II — Prof. Philip Candelas — 16TT

Method of Assessment: No formal assessment; homework completion requirement.
Weight: Unit.
Areas: PT.
Prequel/pre-requisite: String Theory I (HT).

Syllabus: Superstring action, super-Virasoro algebra, RNS model and GSO projection, physical spectrum, type I, IIA, IIB and heterotic strings, D-branes, string dualities.

The Standard Model — Dr Jorge Casalderrey Solana — 16TT

Method of Assessment: No formal assessment; homework completion requirement.
Weight: Unit.

Areas: PT.
Prequel/pre-requisite: Advanced Quantum Field Theory for Particle Physics (HT).

Syllabus: Part I. Weak interactions, weak decays, non-renormalizable Fermi four-point interactions (violation of unitarity), $SU(2) \times U_Y(1)$ gauge symmetry, spontaneous symmetry breaking (masses of gauge bosons), custodial symmetry and Yukawa masses, axial anomaly cancellation, accidental symmetries, renormalizability and power counting, neutrino masses (see-saw mechanism), Higgs phenomenology, Part II. Strong interaction, $SU(3)$ symmetry, Lagrangian, color identities, beta-function and asymptotic freedom, infrared divergences and infrared safety, $e^+e^- \to$ hadrons, R-ratio, parton model (failure with radiative corrections), parton distribution functions, dimensional regularisation, subtraction procedures for calculations of cross-sections, hadron collider phenomenology: event shapes, jets, benchmark processes (Drell-Yan, heavy quarks etc.).

Topics in Quantum Condensed Matter Physics — Prof. John Chalker — 8TT

Method of Assessment: No formal assessment; homework completion requirement.
Weight: 0.5 units.
Areas: CMT.
Prequel/pre-requisite: Quantum Condensed Matter Physics II (HT).

Syllabus: This is a reading course. Under the guidance of the course organiser, students will give presentations based on key papers in quantum condensed matter theory. Some examples of the topics for these presentations are: Kramers-Wannier duality for the Ising model. Feynman's wavefunction approach to superfluid helium. The Haldane conjecture for integer quantum spin chains. Quantum friction. Homotopy and defects. Renormalisation group for Fermi liquids. The Kondo effect and scaling. Fractional statistics. Hartree-Fock and random-phase approximations.

Beyond the Standard Model — Prof. John March-Russell — 16TT

Method of Assessment: No formal assessment; homework completion requirement.
Weight: Unit.
Areas: PT.
Prequel/pre-requisite: Advanced Quantum Field Theory for Particle Physics (HT).

Syllabus: SM precision tests, flavour physics, neutrino physics, strong CP and axions, hierarchy problem, motivations for susy/technicolour/warped extra dimensions and their basic phenomenology, introduction to grand unified theories.

Collisional Plasma Physics — Prof. Felix Parra-Diaz — 16TT

Method of Assessment: Take-home exam.
Weight: Unit.
Areas: Astro.
Prequel: Kinetic Theory (MT), Advanced Fluid Dynamics (HT), Collisionless Plasma Physics (HT).

Syllabus: Collision operators (5 lectures): Fokker-Plank collision operator, conservation properties, entropy, electron-ion and ion-electron collisions, linearized collision operator.

Collisional transport (Braginskii equations) (5 lectures): derivation of Spitzer resistivity and electron heat conduction, ion heat conduction and viscosity.

Resistive MHD (3 lectures): tearing modes, magnetic reconnection.

Introduction to tokamak theory (3 lectures): large-aspect-ratio MHD equilibrium, particle trapping, Pfirsch-Schlueter collision transport regime for electrons.

Astroparticle Physics — Prof. Subir Sarkar — 16TT

Method of Assessment: No formal assessment; homework completion requirement.
Weight: Unit.
Areas: PT, Astro.
Pre-requisites: Quantum Field Theory (MT), General Relativity I (MT).

Syllabus: The Universe observed, constructing world models, reconstructing our thermal history, decoupling of the cosmic microwave background, primordial nucleosynthesis. Dark matter: astrophysical phenomenology, relic particles, direct and indirect detection. Cosmic particle accelerators, cosmic ray propagation in the Galaxy. The energy frontier: ultrahigh energy cosmic rays and neutrinos. The early Universe: constraints on new physics, baryo/leptogenesis, inflation, the formation of large-scale structure, dark energy.

Quantum Field Theory in Curved Space-Time — Dr Tomas Andrade — 16TT

Method of Assessment: No formal assessment; homework completion requirement.
Weight: Unit.
Areas: PT, Astro.
Prequels/pre-requisites: Quantum Field Theory (MT), General Relativity I (MT).

Syllabus: Non-interacting quantum fields in curved space-time (Lagrangians, coupling to gravity, spinors in curved space-time, global hyperbolicity, Green's functions, canonical quantization, choice of vacuum). Quantum fields in Anti de Sitter space. Quantum fields in an expanding universe. Unruh effect. Casimir effect. Black hole thermodynamics. Hawking radiation. Interacting quantum fields in curved space-time. Effective action, heat kernel and renormalization. Holographic principle.

C Case Studies

The following table details some examples of possible pathways through the Programme. These case studies are for illustrative purposes only and show the breadth and diversity of the programme. Many other paths through the course are possible — and in fact much more eclectic or more generalist selections of courses may be appropriate for students who have not settled on a specialisation they intend to pursue eventually. Indispensable courses ("core") for each given case study are indicated in bold. 1 unit=16 lectures; at least 10 units have to be taken over three terms. Note that some of the Case Studies below are sufficiently broad to allow multiple pathways within them, however you should ensure that your chosen pathway allows you to fulfil the requirements for the overall number of units and the number of assessed units. Please see the examination conventions for further details of these requirements.

Pathway	*MT*	*HT*	*TT*
“TEORICA UNIVERSALIS” (Generalist Theoretical Physicist) **Core 4.75–5.75 units** Total 10.75-13.25 units	**1. QFT 24** **2-4. *Three of*** **Advanced Quan. Th. 20** **Noneq. Stat. Phys. 24 (4MT, 20HT)** **Kinetic Theory 24** **GR I 16** **Pert. Methods 16**	1-3. *Three of* Advanced QFT 24 Quantum Matter 16 Adv. Fluid Dyn. 16 Soft Matter 16 Collisionless Plasma Physics 16 Cosmology 16	1-3. *Three of* Gauge-String Duality 16 Standard Model 16 QFT in Curved Space 16 Dissertation
“APPLICATA” (Applied Mathematician) **Core 5.5–7 units** Total 10–11 units	**1-2. *Two of*** **Noneq. Stat. Phys. 24 (4MT, 20HT)** **Kinetic Theory 24** **GR I 16** **3. Pert. Methods 16** 4. *One of* **Diff. Geometry 16** Num. Lin. Algebra 16	**1. Adv. Fluid Dyn. 16** 2. *One of* GFD 16 Networks 16 Collisionless Plasma Physics 16 Galactic Dyn. 16 GR II 16 **3. Complex Variables 16**	1-2. *Two of* Complex Systems* 16 Collisional Plasma Physics 16 Astrophysical Gas Dyn. 20 (10HT, 10 TT) Dissertation
“CONTINUA” (Fluid Dynamicist) **Core 4.5 units** Total 10 - 10.5 units	**1. Kinetic Theory 24** **2. Pert. Methods 16**	**1. Adv. Fluid Dyn. 16** 2. *Three of* Soft Matter Phys. 16 Collisionless Plasma Physics 16 GFD 16 Complex Variables 16	1-2 *Two of* Complex Systems* 16 Collisional Plasma Physics 16 Astrophysical Gas Dyn. 20 (10HT, 10 TT) Dissertation
“GEOMETRA” (Mathematician with a physics streak) **Core 5.5 units** Total 10–10.5 units	**1. QFT 24** **2. GR I 16** **3. Diff. Geometry 16** 3. *One of* Groups & Repr. 24 Algebraic Topology 16 Algebraic Geometry 16	**1. String Theory I 16** 2. *One of* Advanced QFT 24 SUSY & SUGRA 24 GR II 16 Geom. Group Theory 16	**1. String Theory II 16** 2. *Two of* CFT 16 Standard Model 16 Beyond the SM 16 QFT in Curved Space 16
“PARTICULATA” (Particle Phenomenologist) **Core 8 units** Total 10–11 units	**1. QFT 24** **2. Groups & Repr. 24** 3. *One of* Stat. Mech. 16 GR I 16 Pert. Methods 16	**1. Advanced QFT 24** **2. SUSY & SUGRA 24** 3. *One of* String Theory I 16 GR II 16 Cosmology 16	**1. Standard Model 16** **2. Nonpert. QFT 16** 3. *One of* String Theory II 16 Beyond the SM 16 QFT in Curved Space 16 Astroparticle Phys. 16

“SUPERCORDULA” (Hard-core String Theorist) **Core 7.5 units** Total 10.5–11 units	**1. QFT 24** **2. Groups & Repr. 24** 3. *One of* Stat. Mech. 16 GR I 16 Pert. Methods 16 Diff. Geometry 16 Algebraic Geometry 16	**1. Advanced QFT 24** **2. String Theory I 16** 3. *One of* SUSY & SUGRA 24 GR II 16 Cosmology 16	**1. String Theory II 16** **2. CFT 16** 3. *One of* Gauge-String Duality 16 Standard Model 16 Beyond the SM 16 QFT in Curved Space 16 Nonpert. QFT 16
“CONDENSATA” (Condensed Matter Theorist) **Core 6.25 units** Total 11.5–12.25 units	**1. QFT 24** **2. Advanced Quant. Th. 20** **3. Noneq. Stat. Phys. 24 (4MT, 20HT)** 4.*One of* Kinetic Theory 24 Topological Quantum Theory	**1. Quantum Matter 16** **2. Soft Matter 16** 3. Advanced QFT 24 4. Adv. Fluid Dyn. 16	1. Topics Quant. CMP 8 2. Topics Soft Matter 8 3. CFT 16
“DURACELLA” (Hard-core Hard Condensed Matter Theorist) **Core 4.25 units** Total 10.75–11.75 units	**1. QFT 24** **2. Advanced Quant. Th. 20** 3. *Two of* Noneq. Stat. Phys. 24 (4MT, 20HT) Kinetic Theory 24 Pert. Methods 16	**1. Quantum Matter 16** 2. *Two of* Advanced QFT 24 String Theory I 16 Adv. Fluid Dyn. 16	**1. Topics Quant. CMP 8** 2-3. *Two of* CFT 16 Gauge-String Duality 16 Nonpert. QFT 16
“MOLLIS” (Soft Condensed Matter Physicist/Biophysicist) **Core 5.5 units** Total 10 units	1. QFT 24 **2. Noneq. Stat. Phys. 24 (4MT, 20HT)** **3. Kinetic Theory 24** 4. Pert. Methods 16	**1. Adv. Fluid Dyn. 16** **2. Soft Matter 16** 3. *One of* Networks 16 Collisionless Plasma 16	**1. Topics Soft Matter 8** 2. Complex Systems 16
“ASTRA-STELLA” (All-round Astrophysicist) **Core 7 units** Total 10–11.5 units	**1. Kinetic Theory 24** **2. GR I 16** **3. Rad. Proc. and High Energy Asto 20** 4. *One of* QFT 24 Pert. Methods 16	**1.Galactic Dyn. 16** **2. Cosmology 16** 3. *One of* Adv. Fluid Dyn. 16 Collisionless Plasma Physics 16 GFD 16	1. **Astrophysical Gas Dyn. 20 (10HT, 10 TT)** 2. Astroparticle Phys. 16 3. *One of* QFT in Curved Space 16 Dissertation

“COSMICOSMICA” (Dedicated Cosmologist) **Core 4 units** Total 10–10.25 units	**1. GR I 16** 2-3. *Two of* QFT 24 Kinetic Theory 24 Pert. Methods 16 Rad. Proc. and High Energy Asto 20	**1. Cosmology 16** **2. GR II 16** 3.Astrophysical Gas Dyn. 20 (10HT, 10 TT) 4. Galactic Dyn. 16	1. QFT in Curved Space 16 **2. Astroparticle Phys. 16**
“GAIA” (Geophysicist/ Climate Physicist) **Core 2 units** Total 10–10.25 units	1. Kinetic Theory 24 2. Noneq. Stat. Phys. 24 (4MT, 20HT) **3. Pert. Methods 16**	**1. GFD 16** 2. Advanced Fluid Dynamics 16 3.*One of* Networks 16 Astrophysical Gas Dyn. 20 (10HT, 10 TT)	1. Complex Systems* 16 2. Dissertation
“PLASMA” (Plasma Theorist) **Core 5.5 units** Total 10–10.25 units	**1. Kinetic Theory 24** 2. Noneq. Stat. Phys. 24 (4MT, 20HT) **3. Pert. Methods 16**	**1. Adv. Fluid Dyn. 16** **2. Collisionless Plasma Physics 16** 3. *One of* Astrophysical Gas Dyn. 20 (10HT, 10 TT) Complex Variables 16 Dissertation	**1. Collisional Plasma Phys. 16** 2. *One of* Dissertation Astrophysical Gas Dyn. 20 (10HT, 10 TT)

* Please note that courses marked with an * may not be offered in 2016–17.

D Suggested Dissertation Topics

Lattices: from roots to string compactifications

Supervisor: Andreas Braun (`andreas.braun@maths.ox.ac.uk`)

Abstract: A lattice is a free abelian group of finite rank. One can think of a lattice as a discrete subset of a vector space. You can picture this as a type of grid.

Lattices appear in many instances in theoretical physics. For example, the gauge theories used in particle physics rest on the theory of simple Lie algebras, which is in turn based on the corresponding root and weight lattices. Similarly, there is a great number of constructions in string theory employing lattices. Being able to compute with lattices is hence a valuable tool with a wide range of applications.

In mathematics, there are many powerful and surprisingly simple results which govern existence, uniqueness, and embeddings of lattices.

In this project, the student should learn the theory and in particular the computational tools to handle lattices and lattice embeddings. The purpose of this dissertation is to apply those tools to a concrete problem where such techniques allow to classify all string compactifications of a specific class.

Prerequisites: although some knowledge of gauge and string theories, complex algebraic geometry, cohomology groups etc.. would be helpful, this project can be undertaken without any specific prerequisites. This project is appropriate for someone who is taking the course on Groups and Representations.

Students wishing to undertake this dissertation should arrange a meeting with Dr Braun to discuss the details and scope of this dissertation. Although this project can be undertaken with minimal prerequisites, a successfull completion will actively contribute to research.

References:

1. R. Slanski *"Group Theory for unified model building"*, Physics Reports, 1981
2. J.H. Conway, N.J.A. Sloane *"Sphere packings, Lattices and Groups"*, Springer, ISBN: 978-1-4757-2018-1
3. V.V. Nikulin, *"Integral Symmetric Bilinear Forms and some of their Applications"*, Mathematics of the USSR-Izvestiya, Volume 14, Number 1
4. J.Polchinski, *"Superstring Theory"*, chapters 8.4 and 11.6

Axions and the Strong CP Problem

Supervisor: Joseph Conlon (`joseph.conlon@physics.ox.ac.uk`)

Abstract: Axions arose originally as a solution to the strong CP problem of the Standard Model. This dissertation will review the strong CP problem and explain why axions lead to a solution of it. It will review the basic physics of axions and can then branch off into a number of directions. Depending on the interests of the student(s), it may involve how axions arise in string theory and string compactifications, the phenomenological bounds on axions and how searches for axions are carried out, the extension from the QCD axion to more general axion-like particles and the associated physics of these, or the cosmology of axions and their possible role as dark matter.

References: Chapter 5 and 14 of Raffelt (Stars as Laboratories for Fundamental Physics), and Chapter 10 of Kolb+Turner (The Early Universe) for starting points. Students wishing to do this dissertation are also advised to arrange a meeting with Prof. Conlon who will provide more guidance as to further reading.

Weight: single or double unit dissertation.

Topological Defects in Liquid Crystals

Supervisor: Julia Yeomans (`Julia.Yeomans@physics.ox.ac.uk`)

Abstract: Liquid crystals are characterised by long thin molecules, which can order into many different phases. Singularities, or topological defects correspond to singular points in the order parameter field and can now be controlled by eg optical tweezers to create designed structures with photonic applications. This essay could concentrate on the more mathematical aspects of describing topological defects in liquid crystals or on novel defect phases and recent applications.

References:

1. P.G. de Gennes and J. Prost, *The Physics of Liquid Crystals*, Clarendon Press 1995.
2. N.D. Mermin, *Topological theory of defects in ordered media*, Rev. Mod. Phys. 51 591 (1979).

3. Gareth P. Alexander, Bryan Gin-ge Chen, Elisabetta A. Matsumoto, Randall D. Kamien, *Disclination Loops, Hedgehogs, and All That*, Rev. Mod. Phys. 84 (2012) 497.

Superfluidity in helium-3

Supervisor: John Chalker (`John.Chalker@physics.ox.ac.uk`)

Abstract: In fermion systems, superconductivity or superfluidity arises from pairing of fermions followed by condensation. The simplest possibility is for the pairs to have zero relative angular momentum ('s-wave pairs'), and all of the early experimental examples were of this type. Helium-3 is interesting as the first case discovered of spin-one, p-wave pairs.

References:

1. A. J. Leggett, Rev. Mod. Phys. 47, 331 (1975).

Weight: Single unit.

The fractional quantum Hall effect

Abstract: The discovery of the fractional quantum Hall effect started a new era in physics, with ramifications that are still under exploration. Its remarkable features include quasiparticles with factional charge and with quantum statistics that are not those of either fermions or bosons.

Supervisor: John Chalker (`John.Chalker@physics.ox.ac.uk`)

References:

1. S. M. Girvin, arXiv:cond-mat/9907002 published in: Topological Aspects of Low Dimensional Systems, ed. A. Comtet, T. Jolicoeur, S. Ouvry, F. David Springer-Verlag, Berlin, 2000)

Weight: Single unit.

Equations of state in a strong magnetic field

Adviser: Peter A Norreys (`Peter.Norreys@physics.ox.ac.uk`)

Abstract: The equations of state for matter on the surface of pulsars, neutron stars and white dwarfs are strongly influenced by the magnetic field strength there. The appropriate domain for electron degeneracy and for Landau quantization has been calculated for the density-temperature domain relevant to these extreme conditions in the literature. The student will explore the conditions for a strong Landau quantization, for magnetic fields in the domain of up to 10 MT and beyond. The student will also formulate the equations of state in terms of those that can potentially be realized in laboratory plasmas using next generation laser facilities.

References:

1. Astrophysical Journal 374, 652 (1991)
2. Reviews of Modern Physics 73, 629 (2001)
3. Physics of Plasmas 12, 052115 (2005)

Slowing or Stopping of Light Via Dispersion Management

Supervisor: Robert A. Van Gorder (`Robert.VanGorder@maths.ox.ac.uk`)

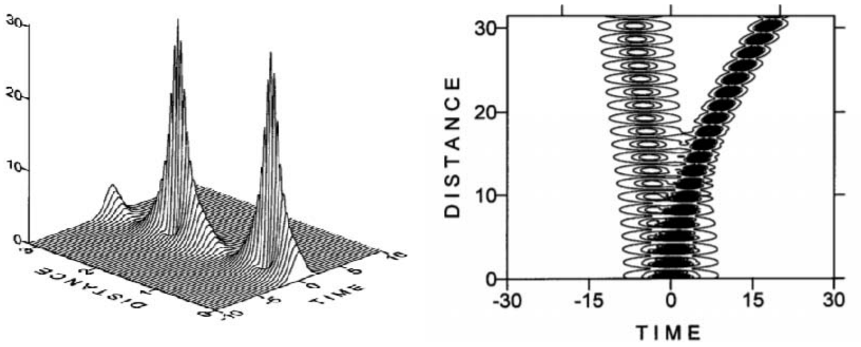

Figure 1: Two DM solitons. Bound state formation and decay with Raman self-scattering effect. Taken from [10].

Abstract: Dispersion management (DM) is a technique used in nonlinear optics (theory and experiment) to modify the properties of light waves [1] (see Fig. 1), often with the goal of allowing optical solitons to travel long distances without dispersal [2]. DM has also been applied to modify the propagation of matter waves [3]. While DM is usually employed to reinforce light waves to allow long distance optical soliton transmission, in this project we shall consider the slowing or stopping of light. Experiments over the past 20 years have demonstrated that light can be slowed, stopped, and then sent along again, through a variety of mechanisms [4,5,6,7,8]. We shall (theoretically) consider doing something similar, through the use of DM. Mathematically, this will involve the study of solitary wave solutions to a nonlinear Schrödinger (NLS) equation, and in particular the role a time-variable potential plays in modifying such waves. For an example of DM applied to NLS, see [9,10].

Prerequisites: Experience with PDEs and nonlinear ODEs: analytic methods and basic familiarity with Matlab or the equivalent. Additional mathematical tools or physical knowledge of the area are not essential at the outset, and can be picked up over the course of the project.

Units: While I would prefer a two-unit project, as this produces the best work (and increases the possibility of obtaining publishable results), a one-unit project can be possible.

1. T. I. Lakoba, J. Yang, D. J. Kaup, and B.A. Malomed, Optics Communications 149 (1998) 366.
2. D. S. Govan, W. Forysiak, and N. J. Doran, Optics Letters 23 (1998) 1523.
3. B. Eiermann et al., Physical Review Letters 91 (2003) 060402.
4. C. Liu, Z. Dutton, C. H. Behroozi, and L. V. Hau, Nature 409(6819) (2001) 490.
5. M. F. Yanik and S. Fan, Physical Review Letters 92 (2004) 083901.
6. O. Kocharovskaya, Y. Rostovtsev, and M. O. Scully, Physical Review Letters 86(4) (2001) 628.
7. D. E. Chang, A.H. Safavi-Naeini, M. Hafezi, and O. Painter, New Journal of Physics 13 (2011) 023003.
8. T. Baba, Nature Photonics 2 (2008) 465.
9. V. N. Serkin and A. Hasegawa, Journal of Experimental and Theoretical Physics Letters 72 (2000) 89.
10. V. N. Serkin and A. Hasegawa, Physical Review Letters 85 (2000) 4502.

Wave Propagation in 2D Granular Crystals and Shallow Water Equations

Supervisor: Robert A. Van Gorder (`Robert.VanGorder@maths.ox.ac.uk`)

Abstract: A granular crystal is an ordered closely packed arrays of elastically interacting particles, such as spheres [1,2]. Granular crystals in 1D, 2D, or 3D are useful in a variety of applications, such as shock and energy absorbing layers, actuating devices, acoustic lenses, acoustic diodes, and sound scramblers [2]. In the study of waves in 1D granular chains, there exist analytical results which involve converting the governing nonlinear ODE system into a single nonlinear PDE and then solving the PDE [3]. Naturally, there are many circumstances for which such approximations loose validity; however, the PDE approximations do allow one to recover reasonable approximations to solitary waves and breathers in the 1D granular chain, when the PDE reduction is valid [4]. Despite the interest in 2D and 3D granular crystals, analogous analytical results are scarce. In this project, we will attempt to arrive at approximate PDE models for wave propagation in 2D granular crystals. Of particular interest to us is the fact that the variety of patterns seen due to waves in 2D granular crystals is much more diverse than we see in 1D granular chains, with Y-shaped, V-shaped, X-shaped, or other waves appearing [2,5]. Such waves have actually been observed in integrable $2+1$ PDEs obtained to study shallow water waves [6] (see Fig. 2), and hence PDE models from that literature might serve as motivation for some of the approximating PDE models we seek.

Prerequisites: Experience with PDEs and nonlinear ODEs: analytic methods and basic familiarity with Matlab or the equivalent. Additional mathematical tools or physical knowledge of the area are not essential at the outset, and can be picked up over the course of the project.

Units: While I would prefer a two-unit project, as this produces the best work (and increases the possibility of obtaining publishable results), a one-unit project can be possible.

1. M. A. Porter, P. G. Kevrekidis, and C. Daraio, Physics Today 68(11) (2015) 44.
2. A. Leonard, C. Chong, P. G. Kevrekidis, and C. Daraio, Granular Matter 16(4) (2014) 531.
3. V. F. Nesterenko, Dynamics of Heterogeneous Materials (Springer, New York, 2001).
4. G. Theocharis, N. Boechler, and C. Daraio. "Nonlinear periodic phononic structures and granular crystals." Acoustic Metamaterials and Phononic Crystals. Springer Berlin Heidelberg, 2013. 217-251.
5. A. Merkel, V. Tournat, and V. Gusev, Ultrasonics 50(2) (2010) 133.
6. M. Ablowitz and D. Baldwin, Physical Review E 86 (2012) 036305.

Gross-Pitaevskii Equation on a Riemannian Manifold

Supervisor: Robert A. Van Gorder (`Robert.VanGorder@maths.ox.ac.uk`)

Abstract: After standard scalings, the non-dimensional form of the Gross-Pitaevskii (GP) equation reads

$$i\Psi_t + \triangle\Psi = \left(\epsilon V(\mathbf{x}) + \kappa|\Psi|^2\right)\Psi\,, \tag{1}$$

where $\mathbf{x} \in \mathbb{R}^n$, $\Psi = \Psi(\mathbf{x}, t)$ defined as a map $\Psi : \mathbb{R}^n \times \mathbb{R} \to \mathbb{C}$ giving a complex wave function, $\epsilon \in \mathbb{R}$ is a constant, $V(\mathbf{x})$ defined as $V : \mathbb{R}^n \to \mathbb{C}$ a complex potential function (although most often it is taken to be real, viz., $V : \mathbb{R}^n \to \mathbb{R}$), and $i^2 = -1$. By $\triangle$ we denote the Laplacian operator on $\mathbb{R}^n$, while $|\cdot|$ denotes the complex modulus. When $V \equiv 0$ we have the cubic nonlinear Schrödinger (NLS) equation, for which case

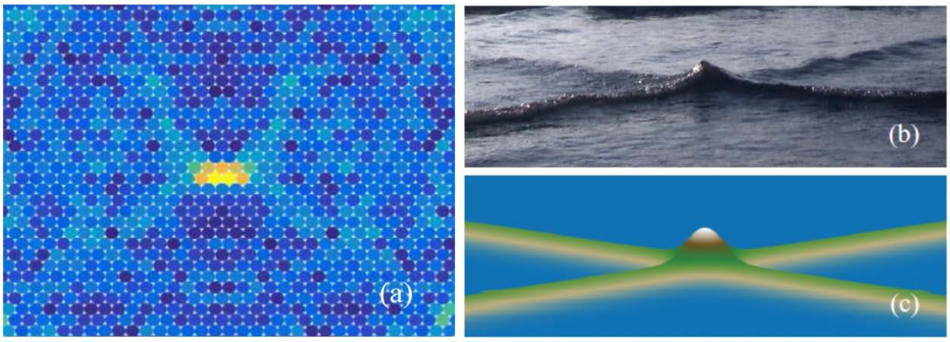

Figure 2: Waves in (a) simulation of 2D granular crystal with hexagonal packing, (b) shallow water, (c) simulation of shallow water via a solution to a Kadomtsev-Petviashvili equation. (a) taken from my ongoing work, (b) and (c) taken from [7].

the constant κ is either $\kappa = +1$ (the defocusing case) or $\kappa = -1$ (the focusing case), or $\kappa = 0$ (from which ones recovers the linear Schrödinger equation).

We shall be concerned with the generalization of the GP equation to the case where the underlying spatial structure is that of a more general manifold than $\mathbb{R}^n$. To this effect, let us consider an n-dimensional manifold $\mathcal{M}$. By $\triangle_{\mathcal{M}}$ we denote the Laplace-Beltrami operator on $\mathcal{M}$. Consider a wave function $\Psi : \mathbb{M} \times \mathbb{R} \to \mathbb{C}$ such that $\Psi \in C^2(\mathcal{M})$ in space and $\Psi \in C^1(\mathbb{R})$ in time. Then, the non-dimensional form of the GP equation defined over the space $\mathcal{M}$ is given by

$$i\Psi_t + \triangle_{\mathcal{M}}\Psi = \left(\epsilon V(\mathbf{x}) + \kappa|\Psi|^2\right)\Psi\,. \tag{2}$$

Here, the potential function V is defined over the manifold, as appropriate for the application at hand. It is assumed to be time-independent for our interests, although time-dependent potentials could also be considered. If we assume that $\mathcal{M}$ is a differentiable manifold with Riemannian metric g on $\mathcal{M}$, then we refer to $(\mathcal{M}, g)$ as a Riemannian manifold.

Equation (2) and related equations have been studied when $V \equiv 0$; for some theoretical results see [1,2,3,4]. However, the potential V is useful and sometimes essential when attempting to study certain phenomenon, such as Bose-Einstein condensates (BECs) [5,6]. Therefore, we shall be interesting in studying (2) under non-zero V, for various choices of $(\mathcal{M}, g)$. There are a number of directions one can take, and the precise focus of the project will be agreed on after consultation with the student. Stability of BECs is a physically relevant topic [7,8,9], and one might consider how the curvature of the underlying space will modify stability properties of the BEC.

Prerequisites: Experience with PDEs and nonlinear ODEs: analytic methods and basic familiarity with Matlab or the equivalent. Knowledge of differential geometry or topology, or an interest in learning a few results in these areas, could prove useful. Additional mathematical tools or physical knowledge of the area are not essential at the outset, and can be picked up over the course of the project.

Units: Only a two-unit project is feasible for this choice.

1. N. Burq, P. Gérard, and N. Tzvetkov, American Journal of Mathematics, 126(3) (2004) 569.
2. Z. Hani, Communications in Partial Differential Equations 37(7) (2012) 1186.
3. A. D. Ionescu and B. Pausader, Communications in Mathematical Physics 312(3) (2012) 781.
4. Z. Hani and B. Pausader, Communications on Pure and Applied Mathematics 67(9) (2014) 1466.

5. K. Mallory and R. A. Van Gorder, Physical Review E 92 (2015) 013201.
6. G. Karali and C. Sourdis, Archive for Rational Mechanics and Analysis 217 (2015) 439.
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8. E. A. Donley et al., Nature 412(6844) (2001) 295.
9. J. C. Bronski et al., Physical Review E 63 (2001) 036612.

Hooke's Atom in Higher Dimensions

Supervisor: Robert A. Van Gorder (`Robert.VanGorder@maths.ox.ac.uk`)

Abstract: Hooke's atom (also harmonium or hookium, in some literature) is an artificial helium-like atom where the Coulomb electron-nucleus interaction potential is replaced by a harmonic potential [1,2]. The harmonic potential used to describe the electron-nucleus interaction follows from Hooke's law, hence the name. While artificial, the atom is useful as it gives an exactly solvable ground-state many-electron problem that includes electron correlation [3]. It provides insight into quantum correlation (albeit in the presence of a non-physical nuclear potential) and can act as a test system for judging the accuracy of approximate quantum chemical methods for solving the Schrödinger equation [4,5].

The study of hydrogen-like atoms on spaces of dimension greater than three has been of some interest (see [6,7,8,9,10], and many references therein). One can attempt similar results for analogues of the helium atom [11,12], but even on $\mathbb{R}^3$ the helium atom is not exactly solvable. Therefore, we are motivated to consider a simpler model which still mathematically gives a ground-state many-electron problem that explicitly includes electron correlation, which leads us to a study of Hooke's atom on a manifold. There are multiple things that can be done here, and the project specifics can be tailored to the interests of the student.

Prerequisites: Experience with PDEs and nonlinear ODEs: analytic methods and basic familiarity with Matlab or the equivalent. Knowledge of differential geometry or topology, or an interest in learning a few results in these areas, could prove useful. Quantum mechanics knowledge will be helpful for motivating the problem. Additional mathematical tools or physical knowledge of the area are not essential at the outset, and can be picked up over the course of the project.

Units: While I would prefer a two-unit project, as this produces the best work (and increases the possibility of obtaining publishable results), a one-unit project can be possible.

1. J. Cioslowski and K. Pernal, The Journal of Chemical Physics 113 (2000) 8434.
2. N. R. Kestner and O. Sinanoglu, Physical Review 128(6) (1962) 2687.
3. S. Kais, D. R. Herschbach, and R. D. Levine, The Journal of Chemical Physics 91 (1989) 7791.
4. S. Kais et al., The Journal of Chemical Physics 99 (1993) 417
5. M. Taut, Physical Review A 48(5) (1993) 3561-3566.
6. V. Aquilanti, S. Cavalli, and C. Coletti, Chemical Physics 214 (1997) 1.
7. S. Nouri, Phys. Rev. A 60 (1999) 1702.
8. S. Bellucci, A. Nersessian, and A. Yeranyan, Phys. Rev. D 70 (2004) 045006.
9. R. A. Van Gorder, Journal of Mathematical Physics 51 (2010) 122104.

10. R. A. Van Gorder, Journal of Mathematical Chemistry 50 (2012) 1420.
11. M. Dunn and D. K. Watson, Few-Body Systems 21(3-4) (1996) 187-209.
12. J. C. Carzoli, M. Dunn, and D. K. Watson, Physical Review A 59 (1999) 182.

Fluctuation and Relaxation in Stellar Systems

Adviser: James Binney (`james.binney@physics.ox.ac.uk`)

Abstract: Fluctuations in the gravitational field around its mean-field value drive the evolution of globular clusters. Traditionally the fluctuations are considered to arise from many 2-body encounters. Explain why Poisson fluctuations in density provide a better starting point. Using this model obtain a order-of-magnitude estimate of the relaxation time of a spherical cluster. If time permits sketch computation of diffusive flux through action space for case of isochrone model.

Relevant courses: Kinetic Theory (MT), Galactic and Planetary Dynamics (HT).

References:

1. Binney & Tremaine, *Galactic Dynamics.* Princeton U Press, 2008 (especially Ch. 7)
2. Ciotti & Binney, *Two-body relaxation in modified Newtonian dynamics*, MNRAS, 351, 285, (2004)
3. Chavanis, *Kinetic theory of long-range interacting systems with angle-action variables and collective effects*, Physica A, 391, 3680 (2012)

Dynamics of extrasolar planets

Adviser: Caroline Terquem (`caroline.terquem@physics.ox.ac.uk`)

Abstract: A significant number of the extrasolar planets detected so far have orbital characteristics very different from those of the planets in our Solar system. The dissertation could focus on some particular characteristic (orbital eccentricity, or orbital period, or inclination of the orbital plane with respect to the stellar equatorial plane, etc.), and summarise the observations and the theories/models which have been put forward to try to account for these observational facts.

References:

1. J. N. Winn & D. C. Fabrycky, *The occurrence and architecture of exoplanetary systems*, Annual Review of Astronomy and Astrophysics, 2015

Instabilities in collisionless astrophysical plasmas

Adviser: Alexander Schekochihin (`alex.schekochihin@physics.ox.ac.uk`)

Abstract: Any local flows of matter or energy in collisionless (or weakly collisional) plasmas cause these plasmas to develop local pressure anisotropies, which provide a source of free energy to very vigorous instabilities. In unmagnetised plasmas, these are known under the general moniker of Weibel instabilities and are believed to be responsible for magnetogenesis in collisionless shocks and shear flows. In magnetised plasmas, the pressure anisotropies develop with respect to the local direction of the magnetic field. The result is that magnetic tension force or magnetic pressure can effectively become negative in such plasmas, giving rise to the firehose and mirror instabilities. The role of these instabilities in the dynamics of astrophysical plasmas (in environments such as intergalactic medium, accretion discs, supernova shocks)has been the subject of much recent interest and research, much of it due to heavy-duty kinetic simulations becoming possible on modern computers. This dissertation will examine how pressure anisotropies arise and how to construct the linear theory of the relevant instabilities. If time and energy are left after that, nonlinear theory of the firehose and mirror can also be studied. There will be considerable opportunity for the student to choose their own path through the relevant topics and the literature. While most of the material can be learned from existing literature (both classic and recent), there is potential for some research-level calculations.

Relevant Courses: Kinetic Theory (MT), collisionless Plasma Physics (HT).

References:

1. Lecture notes: **http://www-thphys.physics.ox.ac.uk/people/AlexanderSchekochihin/notes/LESHOUCHES15/** (typed version available on demand)
2. A selection of research articles.

Hydrodynamic and MHD turbulence

Adviser: Alexander Schekochihin (`alex.schekochihin@physics.ox.ac.uk`)

Abstract: Kolmogorovs 1941 scaling theory of developed turbulence. Structure of statistical correlations of an isotropic vector field (fluid velocity). von Karman-Howarth equations and the exact scaling law for 3rd-order moments (the 4/5 law). Theory of intermittency: Kolmogorov and She-Leveque.

If students time and energy permit, this dissertation can also cover the theory of MHD turbulence (or, alternatively, the student can skip some of the hydro topics and skip to MHD):

Scaling theories: Goldreich-Sridhar theory, critical balance, dynamic alignment. Weak turbulence theory for Alfven waves. Intermittency models and further refinements. (These latter topics contain some potential for research-relevant contributions.)

Other optional topics that can be covered in addition or instead of MHD: Application of the critical balance principle to rotating and stratified turbulence. Kolmogorov-style theory for turbulence in kinetic (collisionless) plasma.

Relevant Courses: a course in fluid dynamics; MHD part of Advanced Fluid Dynamics (HT) or equivalent if the student wishes to cover MHD turbulence.

References:

1. Lecture notes: http://www-thphys.physics.ox.ac.uk/people/AlexanderSchekochihin/notes/SummerSchool07/
2. L. D. Landau & E. M. Lifshitz, *Fluid Mechanics*, Butterworth-Heinemann 1995 (Sec 33, 34)
3. U. Frisch. *Turbulence.* The Legacy of A. N. Kolmogorov. CUP 1995
4. P. A. Davidson. *Turbulence An Introduction for Scientists and Engineers.* OUP 2004.
5. A selection of research articles on MHD turbulence and other topics.

Solvable models for passive turbulent fields

Adviser: Alexander Schekochihin (`alex.schekochihin@physics.ox.ac.uk`)

Abstract: Normally it is (or has so far been) impossible to obtain analytic solutions for correlation functions in turbulent systems. However, for a class of models, analytical treatment is possible: those concern the turbulent advection of scalar and vector fields in an imposed random flow most often white-in-time Gaussian random velocity field is used, as a far-fetched but solvable model of turbulent flow. Exact analytical results can be obtained for this model and it is remarkable how well they tend to work. The two main applications are the advection of a scalar, describing turbulent mixing of a temperature field in a fluid (or perhaps of the concentration of an admixture), and the advection of a vector, describing the evolution of a weak magnetic field in a turbulent conducting fluid. The latter is a model for the so-called turbulent dynamo amplification of mean magnetic energy via random stretching and tangling by a turbulent flow, believed to be responsible for the origin of cosmic magnetism (dynamically strong tangled magnetic fields observed in the interstellar and intergalactic medium, on the surface of the Sun and in many other places). This dissertation will help the student learn both the physics of passive advection and a suite of analytical techniques for handling stochastic systems. While most of the material is standard, there is some potential for research-level calculations, which can be attempted if the student so desires.

Relevant Courses: Nonequilibrium Statistical Physics (MT), a course in fluid dynamics, MHD part of Advanced Fluid Dynamics (HT) or equivalent.

References:

1. Lecture notes: ask supervisor.
2. Ya. B. Zeldovich, A. A. Ruzmaikin & D. D. Sokoloff, *The Almighty Chance* (World Scientific 1990)
3. N. G. van Kampen, *Stochastic Processes in Physics and Chemistry* (Elsevier 1992)
4. A selection of research articles.

Stellarator physics

Adviser: Felix Parra Diaz (`felix.parradiaz@physics.ox.ac.uk`)

Abstract: Stellarators are one of the most clever ideas proposed for magnetic confinement fusion energy, but it has taken decades to get them to be competitive when compared with their main competitor, the tokamak. The reasons for this delay are fundamentally theoretical: 1) it is not clear whether our current description of the stellarator magnetic fields is appropriate, and 2) it is possible to prove that a stellarator that perfectly confines charged particles does not exist, although it is also possible to show that one can get as close to perfect confinement as desired. The student will study these subtleties, and will learn how the stellarator theory community has built on this knowledge to construct one of the most exciting current experiments: Wendelstein 7X in Germany, which started operations this year.

Relevant Courses: Kinetic Theory (MT), Advanced Fluid Dynamics (HT), Collisionless Plasma Physics (HT).

References:

1. A. H. Boozer, Rev. Mod. Phys. 76, 1071 (2004)
2. P. Helander, Rep. Prog. Phys. 77, 087001 (2014)
3. D. A. Garren and A. H. Boozer, Phys. Fluids B 3, 2822 (1991)
4. J. R. Cary and S. G. Shasharina, Phys. Plasmas 4, 3323 (1997)

Gyrokinetics

Adviser: Michael Barnes (`michael.barnes@physics.ox.ac.uk`) or Felix Parra Diaz (`felix.parradiaz@physics.ox.ac.uk`)

Abstract: Gyrokinetics is a powerful technique to describe plasma fluctuations with characteristic frequencies below the Larmor frequency. The power of the technique resides in its choice of phase space coordinates. The student will learn how to derive gyrokinetics, and will study one or two of its applications to fusion or astrophysics.

Relevant Courses: Kinetic Theory (MT), Collisionless Plasma Physics (HT).

References:

1. X. S. Lee, J. R. Myra and P. J. Catto, Phys. Fluids 26, 223 (1983)
2. F. I. Parra and P. J. Catto, Plasma Phys. Control. Fusion 50, 065014 (2008)
3. G.G. Howes et al., Astrophys. J. 651, 590 (2006)
4. Lectures notes by S. Cowley, **http://www-thphys.physics.ox.ac.uk/research/plasma/CowleyLectures/**

MHD equilibrium and stability in axisymmetric magnetic fields

Adviser: Michael Barnes (`michael.barnes@physics.ox.ac.uk`) or Felix Parra Diaz (`felix.parradiaz@physics.ox.ac.uk`)

Abstract: Magnetic confinement fusion requires magnetic field topologies in which the magnetic field lines never get in contact with the solid boundary. This requirement leads to toroidal configurations that must satisfy the MHD equilibrium equations. The most successful of all the possible configurations is the axisymmetric tokamak. The student will study the equilibrium and stability of tokamak plasmas, learning about the most dangerous types of instabilities that limit current experiments and future fusion reactors.

Relevant Courses: Advanced Fluid Dynamics (HT), Collisionless Plasma Physics (HT).

References:

1. J. P. Freidberg, *Ideal MHD*, Cambridge University Press (2014)
2. R. D. Hazeltine and J. D. Meiss, *Plasma Confinement*, Dover Publications (2003)
3. J. W. Connor, R. J. Hastie and J. B. Taylor, Proc. R. Soc. Lond. A. 365, 1 (1979)
4. J. B. Taylor and S. Newton, J. Plasma Phys. 81, 205810501 (2015)

Non-equilibrium Statistical Physics with Action-Reaction Asymmetry

Adviser: Ramin Golestanian (`ramin.golestanian@physics.ox.ac.uk`)

Abstract: The third law of Newton is a fundamental pillar of mechanics on which equilibrium statistical mechanics is built. There are many examples in non-equilibrium physics where this is violated, i.e. the velocity of particle A as a result of its interaction with particle B is not the opposite (negative) of the velocity of particle B as a result of its interaction with particle A. We would like to formulate the non-equilibrium statistical physics of a collection of such particles using a many-body Smoluchowski (or Fokker-Plank) description, and study it using various approximation techniques.

References:

1. R. Soto and R. Golestanian, Phys. Rev. Lett. 112, 068301 (2014)
2. A.V. Ivlev, J. Bartnick, M. Heinen, C.-R. Du, V. Nosenko, and H. Lwen, Phys. Rev. X 5, 011035 (2015)

Motility-induced Phase Separation of Spinners

Adviser: Ramin Golestanian (`ramin.golestanian@physics.ox.ac.uk`)

Abstract: In a collection (or suspension) of active particles, the presence of translational motility works together with excluded volume interactions to create dense clusters that separate from more dilute regions;

a phenomenon that has been called motility-induced phase separation. A key requirement of this phase separation is the presence of translational self-propulsion. Recently, it has been shown that spinning will also lead to a similar effect, but the mechanisms of this transition is currently not known. We would like to formulate this problem using the standard continuum methodology of active matter, by deriving the relevant form of the theory from a microscopic description.

References:

1. ME. Cates and J. Tailleur, Annual Review of Condensed Matter Physics 6, 219-244 (2015)
2. M. Spellings, M. Engel, D. Klotsa, S. Sabrina, A.M. Drews, N.H. P. Nguyen, K.J.M. Bishop, and S.C. Glotzer, PNAS 112, E4642 (2015)

Sloppy Systems

Adviser: Ard Louis (`ard.louis@physics.ox.ac.uk`)

Abstract: Many models in biology, engineering and physics have a very large number of parameters. Often many of these are only known approximately. Moreover, in John von Neuman's famous quip "with four parameters I can fit an elephant, and with five I can make him wiggle his trunk." suggests that only a small set of these parameters are actually relevant? Could there be a fundamental theory of these complex systems that allows us to work out what the key parameters are?

References:

1. Transtrum, Mark K., Machta Benjamin, Brown Kevin, Daniels Bryan C., Myers Christopher R., and Sethna James P. , *Perspective: Sloppiness and Emergent Theories in Physics, Biology, and Beyond*, J. Chem. Phys., Volume 143, Issue 1, (2015)
2. Machta, Benjamin B., Chachra Ricky, Transtrum Mark K., and Sethna James P. , *Parameter Space Compression Underlies Emergent Theories and Predictive Models*, Science, Volume 342, p.604-607, (2013)
3. Gutenkunst, R. N., Waterfall J. J., Casey F. P., Brown K. S., Myers C. R., and Sethna J. P. , *Universally sloppy parameter sensitivities in systems biology models*, PLoS Computational Biology, Volume 3, p.1871-1878, (2007)
4. Waterfall, J. J., Casey F. P., Gutenkunst R. N., Brown K. S., Myers C. R., Brouwer P. W., Elser V., and Sethna J. P. , *Sloppy-model universality class and the Vandermonde matrix*, Physical Review Letters, Volume 97, p.150601, (2006)

Survival of the Flattest or Arrival of the Frequent?

Adviser: Ard Louis (`ard.louis@physics.ox.ac.uk`)

Abstract: Evolution proceeds by mutations to genotypes that in turn change phenotypes (the organism). But since the number of genotypes is much larger than the number of phenotypes, concepts of genetic entropy must enter into the equations, which means methods from statistical mechanics become relevant. In some cases, the entropy means that the phenotypes that end up surviving are not the fittest. Two different scenarios are the "survival of the flattests" and the "arrival of the fittest". Sometimes these are confused, so a clear explanation of how they are similar, and where they differ is needed.

References:

1. Wilke CO, Wang JL, Ofria C, Lenski RE, Adami C, (2001) *Evolution of digital organisms at high mutation rates leads to survival of the attest*, Nature 412: 331333.

2. Iwasa Y (1988), *Free fitness that always increases in evolution*, Journal of Theoretical Biology 135: 265281.
3. Sella G, Hirsh AE (2005),*The application of statistical physics to evolutionary biology*, Proceedings of the National Academy of Sciences of the United States of America 102: 95419546.
4. Barton, NH & Coe, JB (2009), *On the application of statistical physics to evolutionary biology*, Journal of Theoretical Biology, vol 259, no. 2, pp. 317-324.
5. Schaper, S, & Louis A A (2014), *The Arrival of the Frequent: How Bias in Genotype-Phenotype Maps Can Steer Populations to Local Optima PLoS One*, 2014; 9(2): e86635.

Black hole entropy in string theory and holography

Adviser: Andrei Starinets (`andrei.starinets@physics.ox.ac.uk`)

Abstract: Bekenstein and Hawking have shown that black holes can be assigned an entropy whose existence effectively converts the laws of black hole mechanics into the laws of black hole thermodynamics. String theory offers a number of convincing examples explaining the microscopic origin of black hole entropy. The concept can be generalized further to include higher-derivative terms in gravity and is used extensively in modern applications of holography and string theory. The dissertation will review these and related developments in some detail, depending on the interests of the student(s).

References:

1. B. Zwiebach, *A First Course in String Theory*, Cambridge U. Press, Chapter 16 ("String thermodynamics and black holes").
2. M. Ammon and J. Erdmenger, *Gauge/Gravity Duality*, Cambridge U. Press, Chapter 2 ("Elements of gravity").

Students wishing to do this dissertation are also advised to arrange a meeting with Dr Starinets who will provide more guidance as to further reading.

Hawking radiation of black holes

Adviser: Andrei Starinets (`andrei.starinets@physics.ox.ac.uk`)

Abstract: Inspired by work of Zeldovich and Starobinsky, Hawking showed in his classic 1974 paper that black holes emit blackbody radiation at a temperature proportional to the surface gravity at the horizon. The dissertation will review the existing approaches to deriving the Hawking's result including his original calculation as well as more recent method of Parikh and Wilczek and explore applications of these results and further developments, depending on the interests of the student(s).

References:

1. B. Zwiebach, *A First Course in String Theory*, Cambridge U. Press, Chapter 16 ("String thermodynamics and black holes").
2. S.W. Hawking, *Particle Creation by Black Holes*, Commun.Math.Phys. 43, 199 (1975) [Commun. Math. Phys. 46, 206 (1976)].
3. M.K. Parikh and F. Wilczek, *Hawking radiation as tunneling*, Phys. Rev. Lett. 85, 5042 (2000), [hep-th/9907001].

Students wishing to do this dissertation are also advised to arrange a meeting with Dr Starinets who will provide more guidance as to further reading.

Quasinormal modes of black holes and black branes

Adviser: Andrei Starinets (`andrei.starinets@physics.ox.ac.uk`)

Abstract: Eigenmodes of black holes are called quasinormal modes due to the presence of a non-zero imaginary part in the spectrum associated with the existence of the horizon. Quasinormal spectra describe near-equilibrium properties of black holes. More recently, in the context of gauge-string duality, they were shown to coincide with poles of the retarded two-point functions in a dual quantum field theory. The dissertation will review the developments in this field including formal aspects of non-Hermitian boundary value problem or applications, depending on the interests of the student(s).

References:

1. V. Frolov and I. Novikov, *Black hole physics: basic concepts and new developments*, Springer;
2. E. Berti, V. Cardoso and A. O. Starinets, *Quasinormal modes of black holes and black branes*, Class.Quant.Grav. 26, 163001 (2009), [arXiv:0905.2975 [gr-qc]].

Students wishing to do this dissertation are also advised to arrange a meeting with Dr Starinets who will provide more guidance as to further reading.

Supersymmetric quantum mechanics

Adviser: James Sparks (`James.Sparks@maths.ox.ac.uk`)

Abstract: Supersymmetric quantum mechanics is often introduced as a toy model for supersymmetric quantum field theory. However, it also has some surprisingly powerful applications to differential geometry. The aim of this dissertation would be to present an account of supersymmetric quantum mechanics, via both canonical quantization and the path integral, and discuss the Witten index. The supersymmetric quantum mechanics based on a sigma model with target space a Riemannian manifold has Witten index equal to the Euler characteristic of the manifold. One can use this structure to give novel physics proofs of two famous mathematical results: the Morse inequalities, and the Gauss-Bonnet formula.

References:

1. K. Hori et al, *Mirror Symmetry*, (Clay Mathematics Monographs, V. 1) (chapter 10).
2. E. Witten, *Supersymmetry and Morse Theory*, J. Diff. Geom. 17 (1982), 661-692.
3. L. Alvarez-Gaume, *Supersymmetry and the Atiyah-Singer Index Theorem*, Commun. Math. Phys. 90 (1983), 161-173.

E Suggested Oral Presentation Topics

The Path Integral in Quantum Field Theory

Adviser: Joseph Conlon (`joseph.conlon@physics.ox.ac.uk`)

Abstract: The talk will describe Feynman's path integral approach to quantum field theory. The talk should review the action principle and explain the basics of where the path integral comes from and how it is used in calculations. The talk will hopefully also contain a more advanced application, such as to non-perturbative effects in quantum field theory or to the calculation of anomalies.

References: Any good textbook on quantum field theory contains accounts of path integrals

Swimming at Low Reynolds Number

Adviser: Julia Yeomans (`Julia.Yeomans@physics.ox.ac.uk`)

Abstract: Because of their size bacteria and fabricated micro-swimmers swim at low Reynolds number, a regime where the effect of hydrodynamics can be counterintuitive. The talk could include explanations of the Scallop theorem, dipolar flow fields or active swimming in Poiseuille flow.

References:

1. J. Elgeti, R. G. Winkler and G. Gompper, *Physics of microswimmers-single particle motion and collective behavior: a review.*, Reports on Progress in Physics 78 056601 (2015)

One-parameter scaling theory of Anderson localization

Adviser: John Chalker (`John.Chalker@physics.ox.ac.uk`)

Abstract: Anderson localisation concerns the nature of eigenstates of a particle moving in a random potential: states may either extend through the whole system or be trapped in a local region. The phase transition between these two situations can be described using quite a simple application of scaling and renormalisation group ideas.

References:

1. E. Abrahams, P. W. Anderson, D. C. Licciardello, and T. V. Ramakrishnan, Phys. Rev. Lett. 42, 673 (1979)

Poor man's scaling theory of the Kondo effect

Abstract: The Kondo effect is an iconic problem in many-body physics of enduring importance. Poor man's scaling theory provides a simple and appealing way to think about it.

Adviser: John Chalker (`John.Chalker@physics.ox.ac.uk`)

References:

1. P. W. Anderson, J. Phys. C 3, 2436 (1970) L. Kouwenhoven and L. Glazman, arXiv:cond-mat/0104100 published as: Physics World, v. 14, 33

Photon bubble instability

Adviser: Peter A Norreys (`Peter.Norreys@physics.ox.ac.uk`)

Abstract: Radiation dominated plasmas with very strong magnetic fields are found in a number of interesting astrophysical objects. These include blue giant stars as well as accretion powered X-ray sources, such as pulsars and active galactic nuclei. In pulsars, plasma from a binary object are accreted and follow intense magnetic field lines to the poles of the neutron star. The in-flow of matter at the poles is balanced by the radiation pressure where a shock wave is formed. Photon bubbles are formed as a result of density perturbations. A greater flux of radiation is able to pass through the low density regions and results in an imbalance in the radiation pressure. This in turn increases the flow of matter out of the low density regions, along the magnetic field lines. These photon bubbles eventually "pop", resulting in periodic emission of X-rays. The question is: can an experiment be designed in the laboratory to test aspects this concept?

References:

1. Astrophysical Journal 388, 561 (1992)

2. Astrophysics and Space Science 298, 293 (2005)

The physics of a massive gas confined to a spherical box

Adviser: James Binney (`james.binney@physics.ox.ac.uk`)

Abstract: Virial theorem and negative specific heat. Gas initially hot, so radius of the box R ¿¿ Jeans length. Isothermal spherical solutions for fixed mass decreasing temperature. Critical central concentration and core-halo runaway.

Relevant courses: Kinetic Theory (MT), Galactic and Planetary Dynamics (HT).

References:

1. Binney & Tremaine, *Galactic Dynamics*. Princeton U Press, 2008 (Sec 7.3)
2. Lynden-Bell & Wood, *The gravo-thermal catastrophe in isothermal spheres and the onset of red-giant structure for stellar systems*, MNRAS, 138, 495 (1968)

Instabilities in collisionless astrophysical plasmas

Adviser: Alexander Schekochihin (`alex.schekochihin@physics.ox.ac.uk`)

Abstract: This presentation can cover a reduced version of the material proposed for the eponymous Dissertation: for example, explain the emergence and structure of just one of the pressure-anisotropy-driven instabilities.

Relevant courses: Kinetic Theory (MT), Collisionless Plasma Physics (HT), Dissertation on “Instabilities in collisionless astrophysical plasmas”.

Hydrodynamic and MHD turbulence

Adviser: Alexander Schekochihin (`alex.schekochihin@physics.ox.ac.uk`)

Abstract: This presentation can cover a reduced version of the material proposed for the eponymous Dissertation: for example, explain just the Kolmogorov scaling theory and its application to a wave-carrying system (MHD or rotating turbulence.)

Relevant courses: MHD part of Advanced Fluid Dynamics (HT) or equivalent. Dissertation on Hydrodynamic and MHD turbulence

Toroidal MHD equilibria for fusion energy

Adviser: Felix Parra Diaz (`felix.parradiaz@physics.ox.ac.uk`)

Abstract: Magnetic confinement fusion requires magnetic field topologies in which the magnetic field lines never get in contact with the solid boundary. This requirement leads to toroidal configurations that must satisfy the MHD equilibrium equations. The student will explain how these equilibria (tokamaks and stellarators) are achieved.

Relevant courses: Advanced Fluid Dynamics (HT), Collisionless Plasma Physics (HT).

References:

1. J. P. Freidberg, *Ideal MHD*, Cambridge University Press (2014).
2. R. D. Hazeltine and J.D. Meiss, *Plasma Confinement*, Dover Publications (2003).

Whats the right shape for a fusion machine?

Adviser: Felix Parra Diaz (`felix.parradiaz@physics.ox.ac.uk`)

Abstract: The tokamak and the stellarator are the two magnetic fusion concepts with the best performance. These two types of devices have very different shapes, and consequently very different advantages and problems. The student will explain the differences between the two ideas, considering aspects such as stability, transport and current drive.

Relevant courses: Kinetic Theory (MT), Advanced Fluid Dynamics (HT), Colisionless Plasma Physics (HT), Collisional Plasma Physics (TT).

References:

1. J. P. Freidberg, *Plasma Physics and Fusion Energy*, Cambridge University Press (2007).
2. P. Helander, Rep. Prog. Phys. 77, 087001 (2014).

Adiabatic invariants of charged particle motion

Adviser: Felix Parra Diaz (`felix.parradiaz@physics.ox.ac.uk`)

Abstract: Adiabatic invariants are extremely useful to describe the evolution of quasiperiodic orbits. In plasma physics, there are three adiabatic invariants that have proven very useful to understand the evolution of kinetic systems such as fusion devices, the solar wind and the Van Allen belts. The student will explain what adiabatic invariants are, and will choose one application showing how to use them.

Relevant courses: Kinetic Theory (MT), Collisionless Plasma Physics (HT).

References:

1. L. D. Landau and E. M. Lifshitz, *Mechanics. Course of Theoretical Physics. Volume I*, Butterworth-Heinemann (1976).
2. R. D. Hazeltine and J. D. Meiss, *Plasma Confinement*, Dover Publications (2003).
3. M. Kruskal, J. Math. Phys. 3, 806 (1962).
4. R. J. Hastie, J. B. Taylor and F. A. Haas, Annals of Physics 41, 302 (1967).

Origin and Properties of the Van Allen Radiation Belts and Ring Currents

Adviser: Michael Barnes (`michael.barnes@physics.ox.ac.uk`)

Abstract: The Van Allen radiation belts consist of energetic charged particles trapped in the Earths magnetic field. These particles slowly precess around the Earth, leading to a ring current. The aim of this presentation is to explain how the charged particles are trapped in the Earths magnetic field and what causes the precession. The student should calculate the bounce period of the charged particles as well of the precession period.

Relevant courses: Kinetic Theory (MT), Collisionless Plasma Physics (HT).

References:

1. R. Fitzpatricks textbook
   http://farside.ph.utexas.edu/teaching/plasma/lectures1/node19.html http://farside.ph.utexas.edu/teaching/plasma/lectures1/node23.html

Parker Model of Solar Wind and Impact on Solar Evolution

Adviser: Michael Barnes (`michael.barnes@physics.ox.ac.uk`)

Abstract: The solar wind is a stream of plasma continuously flowing out from the sun. This plasma carries solar mass and angular momentum with it, potentially affecting solar evolution. The student should use fluid equations to derive a simple model (the Parker Model) for the solar wind structure and to determine the effect of the solar wind interaction with the interplanetary magnetic field. From these results one can estimate the rate of loss of solar mass and angular momentum due to the solar wind and answer the question of how the solar wind influences solar evolution.

Relevant courses: Advanced Fluid Dynamics (MT), Collisionless Plasma Physics (HT).

References:

1. R. Fitzpatricks textbook
   http://farside.ph.utexas.edu/teaching/plasma/lectures1/node19.html http://farside.ph.utexas.edu/teaching/plasma/lectures1/node23.html

Stochastic Dynamics with Hydrodynamic Interactions

Adviser: Ramin Golestanian (`ramin.golestanian@physics.ox.ac.uk`)

Abstract: Brownian particles in solution interact with each other hydrodynamically. We aim to formulate this interaction within both the Langevin and the Fokker-Planck stochastic descriptions, and show how they affect the dynamics in and out of equilibrium.

References:

1. M. Doi, S.F. Edwards, *The Theory of Polymer Dynamics* (OUP)