Institute of Astronomy
University of Cambridge

Natural Sciences Tripos

Part II Astrophysics

COURSE GUIDE
2020-2021

http://www.ast.cam.ac.uk/teaching/undergrad/partii/

Contents

Welcome to the Institute of Astronomy and to Part II Astrophysics. We hope you will enjoy this course and the friendly and relaxed working environment offered by the Institute of Astronomy.

Those enrolling for Part II Astrophysics in 2020 may either graduate in 2021 or, subject to satisfactory performance – a II.1 in Part II Astrophysics – proceed to Part III. All students proceeding to Part III Astrophysics are required to complete a computational project, either as assessed work for Part II Astrophysics or as additional work over the summer before starting the Part III course. It is assumed that most of you will have studied Physics A, Physics B and Mathematics, in Part IB of the Natural Sciences Tripos, or have taken Part IB of the Mathematical Tripos.

The following sections provide information on the course and on the department. We have not included sections describing general undergraduate life and facilities in Cambridge, because you have been here for two years and know almost all of it already. If you do need any further information at any stage, then please see the Course Secretary. She is normally able to deal directly with most matters, and otherwise will consult or put you in touch with a relevant staff member.

The Aims and Objectives of the Part II Astrophysics Course

The University's stated aims are "to foster and develop academic excellence across a wide range of subjects and at all levels of study". Furthermore, the University aims "to provide an education of the highest calibre at both undergraduate and postgraduate level, and so produce graduates of the calibre sought by industry, the professions, and the public service, as well as providing academic teachers and researchers for the future".

In addition, the specific aims of the Institute of Astronomy are:

- to encourage and pursue research of the highest quality in astronomy and maintain Cambridge's position as one of the world's leading centres in the field,
- to continue to attract outstanding students from all backgrounds,
- to provide an intellectually stimulating environment in which students can have the opportunity to develop their skills and enthusiasms to the best of their potential,
- and to maintain the highest academic standards in undergraduate and graduate teaching and to develop new areas of teaching and research in response to the advance of scholarship.

The Part II Astrophysics course is part of the Natural Sciences Tripos and the topics covered follow on from several in the first two years of the Mathematical Tripos and the Physics part of the Natural Sciences Tripos.

The syllabus includes eight examinable lecture courses split between the Michaelmas and Lent terms. These lecture courses come in two flavours, those which teach the fundamental physics underlying the rest of the course - Relativity, Principles of Quantum Mechanics, Statistical Physics and Astrophysical Fluid Dynamics - and those which apply these concepts to particular astronomical subject areas - Topics in Astrophysics, Introduction to Cosmology, Stellar Dynamics and Structure of Galaxies and Structure and Evolution of Stars. In the Michaelmas term, there is also a non-examinable course giving a general introduction to Astrophysics.

Four lecture courses are unique to Astrophysics. The rest are courses shared with Part II Mathematics or Physics. Michaelmas Term includes courses in Quantum Mechanics (in the Maths Department/online), Structure and Evolution of Stars, Stellar Dynamics and Structure of Galaxies and Relativity (normally in the Physics department but at the IoA/online this year). In the Lent Term there are four courses, Astrophysical Fluid Dynamics (shared with Physics), Introduction to Cosmology, Topics in Astrophysics, and Statistical Physics (in the Maths Department/online). Topics in Astrophysics plays the dual role of familiarising students

students with a range of exciting topics in contemporary astrophysics and developing abilities in physical reasoning and order of magnitude estimates in an astronomical context. In addition to the lectures, students must choose between two options. One option is an extended essay on a topic which is selected from a list of approved titles provided during the Michaelmas term. Advisory sessions are offered for the essays, which must be submitted early in the Easter term. The other option is that students instead complete computational projects from those offered by Part II of the Mathematics Tripos. However, for Part II Astrophysics students, there are two major differences from those taking Part II Mathematics (described later)

Note: The lecture schedule will normally be arranged to accommodate the Part II Mathematics course Classical Dynamics for information (non-examinable).

After completing the year's work students should have:

1. obtained an introduction from the course as a whole to astronomy, astrophysics and cosmology, emphasising the very wide range of applicability of concepts from many areas in physics,
2. obtained experience of independent investigation, either through reading for and preparing the essay or through completion of the computational projects,
3. developed their appreciation of general reasoning in the physical sciences and
4. developed transferable skills. (see details of Journal Club and Public Outreach on page 7).

Preparation for Part II

In order that all students are well equipped for the course, we strongly recommend that students entering from Part IB Physics should complete two computational CATAM projects, which will be marked for feedback at the beginning of Michaelmas Term. Full details of these assignments are emailed to students early in the summer.

Supervisions

The Department organises supervisions on behalf of the Colleges and students are told who their supervisors are within about two weeks of the start of Full Term. There are normally 4 supervisions in groups of two for each course. It is usual for the lecturers in each topic to supervise two pairs of students on their course.
Supervisions may be held in the Meeting Room (Observatory Building, room 1) which may be booked for this purpose, or in offices elsewhere as appropriate. If there are any problems with supervision arrangements, please see the Course Coordinator at the earliest opportunity.

Telescopes

There is no practical element to the course. However, students are encouraged to get involved in the IoA's flourishing Public Outreach Programme (see page 7). Students may also join the Cambridge University Astronomy Society through which they can gain access to various telescopes on the IoA site.

Feedback and Consultation Mechanisms Teaching Committee

During the first two weeks of Michaelmas Term students will be invited to elect one representative from their Part II Astrophysics cohort to attend Teaching Committee meetings. Normally these meetings are held at 2pm on the fourth Thursday of each Full Term.

Questionnaires

These will be distributed at the end of each of the lecture courses so you have an opportunity to tell us what you think of each of them. However, if something needs changing it is then too late to be of use to you, so we encourage you to tell us about it over coffee, or through the Course Secretary or any member of the staff.

There is a meeting so you can give feedback on the course overall towards the end of Lent Term.

Key Contacts

Role	Contact	Phone	Office	Email
Course Coordinator	Cathie Clarke	39087	Hoyle Rm 10	cclarke@ast.cam.ac.uk
CATAM Advisor at IoA	Richard McMahon	37519	Hoyle Rm 49	rgm@ast.cam.ac.uk
Course Secretary	Fatima Rasool	37552	Hoyle Rm 06	ugadmin@ast.cam.ac.uk
Teaching Committee Chair	Christopher Tout	37502	Hoyle Rm 61	cat@ast.cam.ac.uk
Director	Richard McMahon	37519	Hoyle Rm 49	rgm@ast.cam.ac.uk
Director's PA	Susan Hatley	37521	Hoyle Rm 48	hodpa@ast.cam.ac.uk
IoA Librarian	Mark Hurn	37537	Obs Library Office	hurnm@ast.cam.ac.uk
Public Outreach	Carolin Crawford Matt Bothwell	37510 39279	Hoyle Rm 60 Obs Rm 10	csc@ast.cam.ac.uk bothwell@ast.cam.ac.uk

The Course Secretary oversees the day-to-day administration of the course and has copies of all relevant materials such as handouts, examples sheets, past examination papers and formula sheets. She is normally the first point of contact for anything related to the course. If she is not available, then try the Course Coordinator.

Several course-related items are notified directly by email so you should check your email frequently. Please ensure that the Course Secretary has your up-to-date email address. The Part II Noticeboard outside Hoyle Room 6 should also be checked frequently. In addition, it is advisable to give her contact details for your Director of Studies.

Lecture Courses

All lectures that are not designated online will be delivered in the Sackler Lecture Theatre. As circumstances change, courses may switch in either direction between online and in person. [M] indicates that the course is owned by the Maths department.

Michaelmas Term 2020	**Lent 2021**
Dr. D Skinner Principles of Quantum Mechanics, M. W. F. 10 *Online* [M]	Dr. C E Thomas Statistical Physics M. W. F. 9 MR2 [M]
Prof. C Mackay Introduction to Astrophysics Tu. W. Th 10	Prof. G Efstathiou Introduction to Cosmology Tu. W. Th. 10
Prof. M Haehnelt Stellar Dynamics and Structure of Galaxies M. W. 11 Th. 12 *Online*	Prof. C Reynolds Astrophysical Fluid Dynamics M. W. F. 11
Prof. A Challinor Relativity Tu. Th. F. 11 *Online*	Prof. Cathie Clarke and Dr. Oliver Shorttle Topics in Astrophysics M. W. F. 12
Prof. M Pettini Structure and Evolution of Stars Tu. W. F. 12	

For information: Classical Dynamics, Prof. G Ogilive, M.W.F.12 Online - non-examinable

Handouts

Course handouts and examples sheets are normally put on to Moodle and the IoA Part II student web pages. You may find some are in the pigeonholes below the Part II noticeboard outside Hoyle Room 6. Please help yourself to whatever you do not get during the lectures.

Lunchtime Seminars

There is a regular bread-and-cheese lunch, followed by a Seminar, on most Wednesdays in term time. We encourage you to come to these lunches, and the Seminars on a range of astronomical topics which are held in the Sackler Lecture Theatre. There are vending machines in the Hoyle building where snacks and drinks can be purchased at any time. *Currently the lunch is suspended and the talks are accessed by Zoom.*

General Information

Coffee

The IoA staff have coffee (and tea) in the Hoyle building foyer from about 11:00am. There is no charge for coffee for Part II Astrophysics students. Please note that due to Covid 19, arrangements for coffee will be adjusted accordingly.

Journal Club and Social

It is hoped to run the journal club in some form this year

There will be a series of sessions for Part II and Part III students which are designed to build confidence in giving presentations and will also allow socialising between the two year groups. The sessions are run by enthusiastic PhD students who will offer friendly advice on preparing and giving scientific talks (lecturers do not attend!). There will also be wine and nibbles after the talk. Further details of these events are to be confirmed.

Public Outreach

The IoA runs an extremely successful programme of Public Outreach on Wednesday evenings. Student participation is welcome: details available at the Introductory session on 7 October 13:00-13:30 or email bothwell@ast.cam.ac.uk

The format of outreach activities will be modified due to covid 19 as will be explained at the Introductory Session.

Computing

Undergraduate computing facilities are provided by the University Computing Service and the Colleges. Part II Astrophysics students may use the CATAM Public Workstation Facility, details of which are provided in the CATAM handbook.

Library

During Covid 19, only limited access to the library will be possible and borrowing arrangements are modified.

The Institute of Astronomy library holds 8,000 books and 11,000 volumes of astronomical periodicals. Undergraduate students are encouraged to use the library facilities. There is a selection of the recommended textbooks for the courses in the library area on the first floor of the Hoyle building, and a complete set in Library room B in the Observatory building. All books must be used within the confines of the library, and returned to the correct location on the shelves after use. If you need any help ask the Librarian, Mark Hurn, who has an office in the library area in the Observatory Building.

College libraries should also have copies of the recommended text books.

Photocopying

There is a photocopier in the reprographic room (opposite the vending machines), another is located to the right of the stairs to the Sackler Lecture Theatre in the Hoyle building and one in the main library in the Observatory building. Course-related copying is free of charge. For private copying there is a charge of 3p per A4 sheet.

Summer Projects

A summer placement undertaking astronomical research may be of interest, particularly for those considering a Ph.D. in astrophysics. The Institute of Astronomy has only a very modest summer student programme and the few positions available are deliberately targeted at students who are not familiar with the Institute.

It is in your own interests to broaden your experience of research beyond the Institute and obtaining a position elsewhere can be rewarding and benefit future applications for Ph.D. places. Unfortunately, there is no central clearing system for summer positions, and it is a case of making enquires to individual departments/observatories. Many departments in the UK do have positions and those with larger astronomy groups, e.g. Durham, Edinburgh, Oxford, Manchester, are particularly worth investigating. Further afield, several observatories and European groups offer places, e.g. Anglo-Australian Observatory, Australia, Lund Observatory, Sweden.

Some departments/observatories offer funded placements but within the UK it may well be worth making an application for a RAS bursary in collaboration with your target institution/supervisor but you will need to be organised and contact departments in January.

Course Schedules

Introduction to Astrophysics (non-examinable)

***Michaelmas Term, 24 Lectures* - Professor C. Mackay**

Basics Scale and content of Universe: Sizes and masses. Magnitudes, HR diagram, Distance determination, The Sun as a typical star, overview of stellar lifecycles, Newtonian mechanics, orbits, tides, blackbodies, continuum radiation mechanisms, spectra and line radiation. [4]

Telescopes, instruments and observational techniques E-M radiation, gamma-rays, X-rays, UV, visible, IR, mm, radio, transparency of the atmosphere, Major space-based and ground-based facilities, S/N calculations. [2]

White dwarfs and neutron stars WD origin, structure, neutron star origin, structure, discovery of pulsars, observed properties, evolution, beaming, magnetic fields, magnetic dipoles, pulse timing, the utility of pulsaras, gravitational waves. [3]

Close Binary Stars observations, visual binaries, spectroscopic binaries, eclipsing binaries, masses and radii, consequences of a supernova, equipotentials, mass transfer, accretion discs, magnetic stars, evolution in binary systems, cataclysmic variables, the variety of binary systems, stellar mass black holes. [3]

Supernovae and Hypernovae Types, energetics, rates, light curves, spectra, pre-cursors, remnants, radio-active decay, Gamma Ray Bursts (GRBs), discovery, searches, observations, long and short duration GRBs, collapsar-hypernova model, merging of neutron stars and black holes, fireball-shock model, beaming. QSOs as a probe of the intergalactic medium. [3]

Active Galactic Nuclei Discovery, observations, classification, energetics, standard model, host galaxies, reverberation mapping, jets, superluminal motion, unified models, QSO population evolution, black holes in non-AGN galaxies. [3]

Clusters of Galaxies Structure and content, galaxies within them, hot X-ray gas, magnetic fields, dark matter, virial mass, tidal stripping, S-Z effect, cooling flows. [2]

Gravitational Lenses Basic physics, Young diagrams, Einstein rings, critical surface mass density, strong lensing by galaxy clusters, caustics and critical lines, cluster masses, weak lensing, determining the hubble constant, micro-lensing, constraints on halo objects. [2]

Exoplanets Discovery methods, statistics of known exoplanets, pulsar planets, hot jupiters, transits, planet formation, dust, proto-planetary discs, Hill radius, future observations, life. [2]

Books

- Shu, F.H., *The Physical Universe*, chaps. 5-10, University Science Books, California, (1982).
- Accretion Power in Astrophysics (Cambridge Astrophysics) Hardcover – 17 Jan. 2002
  by Juhan Frank, Andrew King, Derek Raine. CUP

† Carroll, B.W. & Ostlie, D.A. An Introduction to Modern Astrophysics (Addison-Wesley) 2017.

Stellar Dynamics and Structure of Galaxies

***Michaelmas Term*, 24 Lectures – Professor M. Haehnelt**

[The topics starred in the Schedules will be lectured, but questions will not be set on them in examinations.]

Orbits in a given potential. Particle orbit in Newtonian gravity; energy, angular momentum. Radial force law - general orbit is in a plane; equations of motion in cylindrical polars. Inverse square law; bound and unbound orbits, Kepler's laws; escape velocity; binary stars; reduced mass. General orbit under radial force law; radial and azimuthal periods; precession. [4]

Derivation of potential from density distribution. Poisson's equation. Description of structure of galaxies. Gravitational potential for spherical systems: homogeneous sphere, modified Hubble profile, power law. Circular orbits; rotation law $V_c(R)$; escape velocities $V_{esc}(R)$. [2]

Nearly circular orbits. Radial perturbations; epicyclic frequency; stability; apsidal precession. Application to pseudo-black hole potential $\Phi = -GM/(r-r_s)$. Vertical perturbations in axisymmetric potential; vertical oscillation frequency; nodal precession. [2]

Axisymmetric density distribution. General axisymmetric solution of $\nabla^2\Phi = 0$. Potential due to ring of matter; series solution; 18-year eclipse cycle. Potential due to thin disc; rotation curves of Mestel's disc; exponential disc. Rotation curve of the galaxy; Oort's constants. Rotation curves of spiral galaxies; need for dark matter. [5]

Collisionless systems. Relaxation time. Estimates for stellar and galaxy clusters. Gravitational drag. The stellar distribution function; collisionless Boltzmann equation. The Jeans equations as moments of the Boltzmann equation. Analogy with fluid equations. Application to mass in the solar neighbourhood (Oort limit). [4]

Jeans Theorem. Application to simple systems in which the distribution function depends only on energy. Useful approximate galactic potentials; polytrope, Plummer's model, isothermal sphere. [3]

Globular cluster evolution. Models of globular clusters. King models. *Models with anisotropic velocity distributions.* Observational tests. [3]

Books

Goldstein *Classical Mechanics*, Addison-Wesley (2nd edition 1980).
† Binney, J. & Tremaine, S.D. *Galactic Dynamics*, Princeton University Press (2008).
Landau & Lifshitz *Mechanics*, Pergamon (3rd edition 1976, reprinted 1994).
† Binney, J. & Merrifield, M. *Galactic Astronomy*, Princeton University Press (1998).
Sparke, L.D. & Gallagher, J.S. *Galaxies in the Universe - An Introduction* CUP (2000) (ISBN 0-521-59740-4)

Principles of Quantum Mechanics

***Michaelmas Term,* 24 Lectures – Dr D. Skinner**

Further information about this course is available on the [Department of Mathematics course pages](). Examples papers are available on the [DAMTP Examples page]().

Dirac formalism
Bra and ket notation, operators and observables, probability amplitudes, expectation values, complete commuting sets of operators, unitary operators. Schrodinger equation, wave functions in position and momentum space. [3]
Time evolution operator, Schrodinger and Heisenberg pictures, Heisenberg equations of motion. [2]

Harmonic oscillator
Analysis using annihilation, creation and number operators. Significance for normal modes in physical examples. [2]

Multiparticle systems
Composite systems and tensor products, wave functions for multiparticle systems. Symmetry or antisymmetry of states for identical particles, Bose and Fermi statistics, Pauli exclusion principle. [3]

Perturbation theory
Time-independent theory; second order without degeneracy, first order with degeneracy. [2]

Angular momentum
Analysis of states ljm> from commutation relations. Addition of angular momenta, calculation of Clebsch-Gordan coefficients. Spin, Pauli matrices, singlet and triplet combinations for two spin half states. [4]

Translations and rotations
Unitary operators corresponding to spatial translations, momenta as generators, conservation of momentum and translational invariance. Corresponding discussion for rotations. Reactions, parity, intrinsic parity. [3]

Time-dependent perturbation theory
Interaction picture. First-order transition probability, the golden rule for transition rates. Application to atomic transitions, selection rules based on angular momentum and parity, absorption, stimulated and spontaneous emission of photons. [3]

Quantum basics
Quantum data, qubits, no cloning theorem. Entanglement, pure and mixed states, density matrix. Classical determinism versus quantum probability, Bell inequality for singlet two-electron state, GHZ state. [2]

Appropriate books
E. Merzbacher Quantum Mechanics, 3rd edition. Wiley 1998
B.H. Bransden and C.J. Joachain Quantum Mechanics, 2nd edition. Pearson
J. Binney and D. Skinner The Physics of Quantum Mechanics. Cappella Archive, 3rd edition
P.A.M. Dirac The Principles of Quantum Mechanics. Oxford University Press 1967, reprinted 2003
S. Weinberg Lectures on Quantum Mechanics. CUP, 2nd ed., 2015
J.J. Sakurai and J.J. Napolitano Modern Quantum Mechanics. CUP 2017

Structure and Evolution of Stars

***Michaelmas Term,* 24 Lectures – Professor Max Pettini**

1. Basic Concepts and Observational Properties
- Course overview
- Mass, Temperature, Luminosity Gravity, composition, Age
- Photometry and stellar colours; Spectra and spectral lines
- Distance: parallax, apparent and absolute magnitudes
- Masses from binary stars
- Temperature: black-body radiation, Wien's Law
- The Hertzsprung-Russell Diagram and spectral classification

2. Stellar Structure
- Timescales; dynamical, thermal nuclear
- Energy generation, thermonuclear reactions
- Energy transport; opacity, radiative and convective transport
- Equations of stellar structure
- Hydrostatic equilibrium, Virial Theorem, Pressure
- Stellar properties as a function of mass, homology
- Degeneracy: Chandrasekar limit

3. Stellar Evolution and the Hertzsprung-Russell diagram
- Pre-main sequence evolution, Hayashi and Henyey tracks
- Post-main sequence evolution: massive stars, supernovae, neutron stars, black holes
- Post-main sequence evolution: low-mass stars, planetary nebulae, white dwarfs, Type Ia supernovae
- Initial mass function

4. Observational Tests and Constraints
- The mass-luminosity relationship
- Stellar abundances
- The most massive stars and stellar winds
- Supernovae

Books

Prialnik, D., An Introduction to the Theory of Stellar Structure and Evolution, Cambridge University Press, 2000, 2nd Edition 2010

Phillips, A.C., The Physics of Stars, Wiley, 2nd Edition, 1999

Ostlie, D.A. & Carroll, B.W., An Introduction to Modern Stellar Astrophysics, Addison-Wesley, 1996, 2nd Edition 2013

Tayler, R.J., The Stars: Their Structure and Evolution, Cambridge University Press, 1994

Green, S. & Jones, M., An Introduction to the Sun and Stars, Cambridge University Press, 2004

Gray, D.F., The Observation and Analysis of Stellar Photospheres, 3rd Edition, Cambridge University Press, 2008

Relativity

***Michaelmas term,* 24 Lectures — Professor A. Challinor**

The topics starred in the Schedules *may* be lectured, but questions will not be set on them in examinations.

Introduction: problems with Newtonian gravity, the equivalence principle, gravity as spacetime curvature.

Foundations of special relativity: Inertial frames, spacetime geometry, Lorentz transformations, length contraction and time dilation, Minkowski line element, particle worldlines and proper time, Doppler effect, addition of velocities, acceleration and event horizons in special relativity.

Manifolds, coordinates and tensors: Concept of a manifold, curves and surfaces, coordinate transformations, Riemannian geometry, intrinsic and extrinsic geometry, the metric tensor, lengths and volumes, local Cartesian coordinates, pseudo- Riemannian geometry, scalar fields, vectors and dual vectors, tensor fields, tensor algebra, covariant differentiation and the metric connection, intrinsic derivative, parallel transport, geodesics.

Minkowski space and particle dynamics: Cartesian inertial coordinates, Lorentz transformations, 4-tensors and inertial bases, 4-vectors and the lightcone, 4-velocity, 4-acceleration, 4-momentum of massive and massless particles, relativistic mechanics, arbitrary coordinate systems.

Electromagnetism: Lorentz force, the current 4-vector, the electromagnetic field tensor and field equations, the electromagnetic 4-potential.

Spacetime curvature: Locally-inertial coordinates, weak gravitational fields, intrinsic curvature, the curvature tensor, the Ricci tensor, parallel transport, geodesic deviation and tidal effects, physical laws in curved spacetime.

Gravitational field equations: the energy-momentum tensor, perfect fluids, relativistic fluid dynamics, the Einstein equations, the weak field limit, the cosmological constant.

Schwarzschild spacetime: static isotropic metrics, solution of empty-space field equations, Birkhoff's theorem, gravitational redshift, trajectories of massive particles and photons. Singularities, radially-infalling particles, event horizons, Eddington- Finkelstein coordinates, gravitational collapse, tidal forces.

Experimental tests of general relativity: precession of planetary orbits, the bending of light.

Friedmann–Robertson–Walker spacetime: the cosmological principle, comoving coordinates, the maximally-symmetric 3-space, the FRW metric, geodesics, cosmological redshift, the cosmological field equations.

***Linearised gravity and gravitational waves:** weak field metric, linearised field equations, Lorenz gauge, wave solutions of linearised field equations.*

Introduction to Cosmology

***Lent Term,* 24 Lectures – Prof G. Efstathiou**

1. Is cosmology science? [1]

   1. Causal structure of space-time: our past light cone
   2. Technology horizon, particle horizon and the `size' of the Universe
   3. Importance of symmetry principles in cosmology
   4. Big problems in cosmology

2. The background cosmology [6]

   1. Symmetric spaces
   2. The Friedmann-Robertson-Walker metric
   3. Energy Momentum Tensor for Perfect Fluid
   4. Friedman equations and geometry of the Universe
   5. Cosmological redshift
   6. Newtonian cosmology
   7. Cosmological constant
   8. de-Sitter space and time-slicing
   9. horizons
   10. distances and age of the Universe

3. Thermal history [5]

   1. The cosmic microwave background (CMB) radiation
   2. Thermal equilibrium: bosons and fermions
   3. Particle content at early times
   4. Neutrinos and neutrino decoupling
   5. Big-bang nucleosynthesis
   6. Relic particles
   7. dark matter
   8. baryon asymmetry
   9. recombination

4. Fluctuations [5]

   1. Newtonian perturbation theory
   2. Fluctuations in the CMB -- Silk Damping
   3. Inflation and the origin of fluctuations
   4. Gravitational waves and tests of inflation
   5. What can we learn from the CMB?
   6. The ΛCDM model
   7. The multiverse
   8. Unanswered questions

5. Observational Probes [4]

   1. Standard candles -- Type 1a supernovae
   2. Standard ruler -- Baryon Acoustic Oscillations
   3. Inverse distance ladder and H_0
   4. Forward distance ladder and H_0
   5. Gravitational lensing
   6. Redshift space distortions
   7. Is ΛCDM consistent with observations?

Statistical Physics

Further information about this course is available on the Department of Mathematics course pages.
Examples papers are available on the DAMTP Examples page.

Lent Term, 24 Lectures – Dr C.E. Thomas

Fundamentals of statistical mechanics
Microcanonical ensemble. Entropy, temperature and pressure. Laws of thermodynamics. Example of paramagnetism. Boltzmann distribution and canonical ensemble. Partition function. Free energy. Specific heats. Chemical potential. Grand Canonical Ensemble. [5]

Classical gases
Density of states and the classical limit. Ideal gas. Maxwell distribution. Equipartition of energy. Diatomic gas. Interacting gases. Virial expansion. Van der Waals equation of state. Basic kinetic theory. [3]

Quantum gases
Density of states. Planck distribution and black body radiation. Debye model of phonons in solids. Bose-Einstein distribution. Ideal Bose gas and Bose-Einstein condensation. Fermi-Dirac distribution. Ideal Fermi gas. Pauli paramagnetism. [8]

Thermodynamics
Thermodynamic temperature scale. Heat and work. Carnot cycle. Applications of laws of thermodynamics.
Thermodynamic potentials. Maxwell relations. [4]

Phase transitions
Liquid-gas transitions. Critical point and critical exponents. Ising model. Mean field theory. First and second order phase transitions. Symmetries and order parameters. [4]

Appropriate books

F. Mandl Statistical Physics. Wiley 1988
R.K. Pathria Statistical Mechanics, 2nd ed. Butterworth-Heinemann 1996
L.D. Landau and E.M. Lifshitz Statistical Physics, Part 1 (Course of Theoretical Physics volume 5). Butterworth-Heinemann 1996
F. Reif Fundamentals of Thermal and Statistical Physics. McGraw-Hill 1965
A.B. Pippard Elements of Classical Thermodynamics. Cambridge University Press, 1957
K. Huang Introduction to Statistical Physics. Taylor and Francis 2001

Astrophysical Fluid Dynamics

***Lent Term,* 24 Lectures – Prof. C Reynolds**

Fluids are ubiquitous in the Universe on all scales. As well as obvious fluids (e.g. the gas that is in stars or clouds in the interstellar medium) a variety of other systems are amenable to a fluid dynamical description - including the dust that makes up the rings of Saturn and even the orbits of stars in the galactic potential. Although some of the techniques of conventional (terrestrial) fluid dynamics are relevant to astrophysical fluids, there are some important differences: astronomical objects are often self-gravitating or else may be accelerated by powerful gravitational fields to highly supersonic velocities. In the latter case, the flows are highly compressible and strong shock fronts are often observed (for example, the spiral shocks that are so prominent in the gas of galaxies like the Milky Way).

In this course, we consider a wide range of topical issues in astronomy, such as the propagation of supernova shock waves through the interstellar medium, the internal structure of stars and the variety of instabilities that affect interstellar/intergalactic gas. These include, perhaps most importantly, the Jeans instability whose action is responsible for the formation of every star and galaxy in the Universe. We also deal with exotic astronomical environments, such as the orbiting discs of gas which feed black holes.

Introduction. The concept of a fluid. Collisional and collisionless fluids. Kinematics. Conservation of mass. Pressure. (Inviscid) momentum equation for a fluid under gravity. Stress tensor and the concept of ram pressure. [2]

Basic concepts of gravity. Poisson's equation. Gravitational potential. The Virial Theorem. [2]

Equation of state. Barotropic relation between pressure and density. Energy equation. Hydrostatic equilibrium. Examples: hydrostatic atmosphere under uniform gravity; self-gravitating isothermal slab; self-gravitating polytropes as simple models of stars, mass-radius relation. [3]

Sound waves. Sound speed: adiabatic and isothermal case. Sound waves in a stratified atmosphere. [2]

Supersonic flows. Rankine-Hugoniot conditions for adiabatic and isothermal shocks. Application to blast waves and supernova remnants. [4]

Bernoulli's equation and its applicability. De Laval nozzle and its relevance to astrophysical jets. Bondi accretion, stellar winds and mass loss. [3]

Fluid instabilities. Convective instability, Schwarzschild criterion. Jeans instability. Rayleigh-Taylor and Kelvin-Helmholtz instability. Thermal instability, Field criterion. [3]

Viscous flows. Linear shear flow. Navier-Stokes equation. Vorticity and energy dissipation in viscous flows. Accretion discs. Steady thin discs. [4]

Magnetohydrodynamics. The ideal MHD equations. Alfven waves. [1]

Recommended books: Clarke, C.J. & Carswell, R.F. Principles of Astrophysical Fluid Dynamics, Cambridge University Press (2014) Landau & Lifshitz, Fluid Mechanics, Pergamon Press (1987)

Further suggestions: Acheson, D. Elementary Fluid Dynamics Oxford University Press (1990)Batchelor, G.K. An Introduction to Fluid Dynamics, Cambridge University Press (1967, reprinted 2000) Lamb, H. Hydrodynamics, Cambridge University Press (6th ed 1932, reprinted 1993)

Topics in Astrophysics

***Lent Term,* 24 Lectures – Prof. C J Clarke, Dr O. Shorttle and IoA/Physics staff**

How do astronomers make deductions about the important physical processes operating in the Universe when they are forced to play the role of passive observer rather than active experimentalist? Despite all the complicated analytical machinery that has been developed to process astronomical data and to perform complex theoretical simulations, there is still a vital role in astrophysics for the order of magnitude estimate in order to sort out the relative importance of different physical effects. This is a skill that is rarely taught and one that is not always easily acquired, even though its mastery generally involves little more than the physics that is taught in the first two years of an undergraduate education.

This course aims to teach a set of skills by looking at a large range of astrophysical phenomena on scales from exoplanets to quasars. The issues to be discussed span well established astronomical truths (and how we know them) as well as a range of topics that are still at the forefront of debate. The lectures will provide an immersion in topics in contemporary astrophysics but the examinable content of the course - and the supervision problem sets - do *not* involve significant factual recall of the lecture content; instead these exercises are designed to develop clear thinking and the ability to make intelligent deductions from information presented.

To provide a vehicle for teaching these skills, the course is divided into two broad themes. The first half of the course considers the multi-faceted applications of Newtonian dynamics and tidal theory to a wide variety of astronomical objects, emphasising the wealth of phenomena that can be understood in terms of a small number of key dynamical concepts. In the second half of the course we consider the basic physics of planet formation and evolution. These core lectures are interspersed with `Guest Lectures' where a number of staff in astronomy departments across Cambridge relate these lectures to cutting edge research.

The scheduling of lecture topics may occasionally deviate slightly from what is set out below except in the case of the Guest Lectures ***TBC for 2020/21***

Lecture 1-3: Timescales and Distributions
Lecture 4: Guest Lecture: C. Tout, Type IA Supernovae
Lectures 5-10 Tides and Dynamics
Lecture: 11 Guest Lecture: M. Wyatt, The Formation of the Moon
Lecture 12: Guest Lecture: V. Belokurov, Tidal stripping in action: the field of streams
Lecture 13-15: The assembly of planets
Lecture 16-17: Where do atmospheres come from and where do they go?
Lecture 18: Guest Lecture: N. Madhusudhan, Exoplanet atmospheres
Lectures 19: Planetary interiors
Lectures 20: Solar system small bodies
Lecture 21: Guest Lecture: A. Bonsor, White dwarf insights into exoplanetary composition
Lecture 22: The formation of moons
Lecture 23: Guest Lecture: D. Queloz, The discovery of extrasolar planets
Lectures 24: Unsolved problems in planet formation and evolution

Recommended books:
There are no textbooks to support the course. However for students who are interested in learning more about some of the topics covered, the following books (in addition to those supporting other Part II Astro. courses) are recommended:

P. Armitage, The Astrophysics of Planet Formation, Cambridge University Press, 2010.
D Catling & J Kasting, Atmospheric evolution on inhabited and lifeless worlds, CUP, 2017
Frank, J., King, A., Raine, D., Accretion Power in Astrophysics, Cambridge University Press, 2002.
F. Mellia High Energy Astrophysics, Princeton University Press, 2009.
D Turcotte, Geodynamics, CUP, 2018
D. Ward-Thompson & A. Whitworth, An Introduction to Star Formation, Cambridge University Press, 2011.

Part II Essays

Natural Sciences Tripos Part II Astrophysics -
In accordance with Regulations 30 (Astrophysics) of the Natural Sciences Tripos (Statutes and Ordinances, p 410 (dated 2017), the Director of the Institute of Astronomy gives notice that each candidate may submit an essay. The essay titles will be published on 19 October.

Assessment

Essay

Students may choose to undertake an extended essay. Please note that before you take Part III Astrophysics, if you choose the essay option, you will be required to complete a CATAM project in the long vacation. The purpose of the essay is to bring students to a closer awareness of the current frontiers of astronomical research, by reading and assimilating research literature addressing problems that have not been completely solved in some limited area of endeavour. The essay should be at the forefront of research and not be merely a summary of the literature (or lecture notes) and the ideas they contain, but should be organized in such a way as to address specifically some issue or issues which the candidate considers to be particularly interesting and important. A critical approach should be adopted and students should not refrain from making their own judgements on the validity or plausibility of the arguments discussed. Back-of-the-envelope calculations and general physical arguments should be made to support those judgements, whenever that is possible.

The regulations require that the essay be submitted to the Examiners not later than the tenth day of the Full Easter Term [Thursday, 6 May]. Late submissions must be submitted via your College Tutor with an accompanying letter of explanation from the Tutor. The length of the essay will be not more than 5,000 words (exclusive of tables, figures, footnotes, appendices, and bibliography). Note that figure captions and table captions do not count towards the total word count. The subject of the essay will be chosen from a list of approved subjects not later than the division of the Michaelmas Term [9 November]. Each candidate will, not later than the end of Full Lent Term [Friday, 19 March] notify the Course Administrator the subject chosen from the list. It is expected that the maximum credit obtainable is equivalent to that for a course of 24 lectures and that it will be added to the credit gained in the written examination.

It is important to realize that marks are awarded by the Examiners not merely for a well written review, which shows that the candidate has understood the issues in question, but also for originality of presentation providing a demonstration that those issues have been thoroughly digested. More credit will be given for an essay containing a thorough, well-reasoned discussion of a relatively small area of the subject than a superficial review of a wide area. Nevertheless, candidates are advised to set their discussion into a wider context, explaining briefly its relevance to other issues. The Examiners will award marks for an up-to-date essay which demonstrates a good physical understanding of the material.

The candidate may choose whatever format and style of writing they prefer although they should be aware that an overly sensational or journalistic style may not suit their subject matter. Note that if the examiners consider that an essay is not sufficiently legible, they have the power to require that it be resubmitted in typescript. The essay should incorporate in-text references with a complete reference list, as found in journal papers in the subject area, at the end.

It is a fundamental tenet of scientific writing that due acknowledgment is given to the work and ideas of others that form the basis of, or are incorporated in, an essay. You must always acknowledge the source of an idea or material you use with a specific reference. Plagiarism, including the use of another individual's ideas, data or text, is regarded as an extremely serious disciplinary offence by the University: for further guidance on what constitutes plagiarism, see http://www.admin.cam.ac.uk/univ/plagiarism/

A list of the essay topics will be posted on the Part II noticeboard outside the Course Secretary's office by the middle of the Michaelmas Term, [not later than 19 October] and she will have further details from the essay supervisors giving brief descriptions for each of them.

All candidates are strongly encouraged to consult the advisor who has been assigned to the essay of choice. They should also be aware that some advisors may be difficult to contact for extended periods over the Easter break, so starting work on the essay no later than the start of the Lent Term is advisable.

Computational Projects

Students may (as an alternative to the essay) complete computational projects selected from those offered in Part II of the Mathematical Tripos. The maximum credit for the projects, which is equivalent to that for a course of the 24 lectures, can be obtained for projects amounting to 16 units. This will generally involve two, or at most three, projects. Fewer units may be offered for proportionally less credit. If more than 16 units are submitted (e.g. if your choice of projects does not fit in the 16 unit total) then your credit will be scaled to bring the number of units back to 16. A full description of the projects on offer, and the number of units ascribed to them, can be found in the CATAM handbook (Mathematical Tripos Part II, Computational Projects). The CATAM handbook also details the required form of the reports and the assessment procedure. For Part II Astrophysics students, there are two major differences from those taking Part II Mathematics:

1. Maximum credit can be obtained by submitting projects amounting to 16 units, and this credit is equivalent to a 24-lecture course (rather than as stated in CATAM sections 1.1 & 2.1.1).
2. While the marking scheme is the same, the scaling of the marks will be carried out to reflect the fact that 16 units corresponds to a 24-lecture course. (The comments regarding the marking for Mathematics students in the third paragraph of CATAM section 2.1 are not relevant.)

All other aspects are as described in the Part II Computational Projects Manual.

There is a CATAM helpline, catam@maths.cam.ac.uk. Please read advice in CATAM Project Handbook Introduction and also read Questions and Answers concerning Part II CATAM projects before submitting a question to the helpline. One Computational Projects lecture is given at the beginning of Michaelmas Term by the various assessors who introduce their projects and answer questions on them. **The lecture is on Wednesday 7 October, 14:00-15:00, details yet to be confirmed.** Further help is available from Professor Richard McMahon at the Institute of Astronomy.

All students who intend to submit computational project reports should notify the Course Secretary by the end of the Full Lent Term (19th March) that they intend to do so. When they have submitted their project reports, they should tell the Course Secretary which ones they have attempted.

Examinations

The topics starred in the Schedules will be lectured, but questions will not be set on them in examinations.

Specific information regarding the examinations will be given in notices posted on the Part II noticeboard outside Hoyle Room 6 and in The Reporter.

The Teaching Committee have recommended to Examiners that, in addition to a numerical mark, extra credit should be available for the completeness and quality of each answer. An alpha quality mark signifies an answer of high quality which is substantially complete. A beta quality mark usually signifies at least half marks. It must be understood that Examiners have discretion in the implementation of these recommendations.

In the examinations candidates will not be required to quote elaborate formulae from memory. It is the responsibility of each student to equip themselves with a suitable calculator (see following notice). A few spare calculators are provided in the examination rooms but only to students whose own calculator has malfunctioned.

Electronic calculators in University examinations, 2020–2021 (Cambridge Reporter 7 Oct. 2020)

The Faculty Boards and other authorities concerned give notice that in the following examinations in 2020–21 candidates will be permitted to take a designated calculator into the examination room:

Natural Sciences Tripos, Part II

This information may be subject to amendment after relevant Reporter has been published
For the above examinations the following calculators marked in the approved manner are permitted:

- CASIO fx 991 (any version)
- CASIO fx 115 (any version)
- CASIO fx 570 (any version)

It is the responsibility of each student to equip themselves with a suitable calculator as described.

Each such calculator permitted in an examination must be marked by the Department in the approved fashion so that they are clearly identified as being permitted during the examination.

No other calculator may be brought into the examination.

Sale of approved calculators

Approved calculators, marked in the approved fashion, will be on sale from:

- Department of Physics, Bragg Building (Natural Sciences Tripos)

Approved calculators bought elsewhere will need to have the approved marking applied by the Department.

Special Examination Arrangements

Any student who believes there are circumstances that require special treatment by the examiners must ensure that this information is communicated to the Course Secretary by their College at the earliest opportunity, see
http://www.admin.cam.ac.uk/students/studentregistry/exams/undergraduate/

The form of the examination

There will be four papers in total of three hours each. Each of these four papers consists of a question from each of the eight courses, which carry equal total exam credit. Candidates may attempt not more than six questions on each paper and have free choice of these.

Each question will consist of a Part (i) and a Part (ii). Part (i) will be designed to be very straightforward and to take about half as long to answer as Part (ii). In a given question, Part (i) and Part (ii) may or may not be directly related and will be given separate quality marks. Previous examination papers can be found here. Last year's report by the External Examiner is here.

The examiners may, at their discretion, further examine a candidate viva voce.

Examination Results

Examinations are a University matter and covered by strict regulations. Whether you have a complaint or not, you should not, under any circumstances, seek to discuss your examination result with your examiners. The University has a standard procedure for dealing with complaints about examination results.

Any complaints or requests for reconsideration must be made in writing by your College (usually via your Senior Tutor) to the Chairman of the Examiners. You should therefore discuss the matter with your College Tutor who will advise you further. You should note that any investigation by the University will usually confine itself to seeing that the examiners acted correctly (for example that all the marks you received were entered into the mark book) and not try to second guess the examiners by re-marking your papers.

Criteria for Marking Pt II Astrophysics Examination Papers

The Institute of Astronomy Teaching Committee recommends that the NST Part II Astrophysics examiners mark the written examinations and assess their contribution to the overall degree class according to the following criteria.

First class marks

A candidate placed in the first class will be able to demonstrate a full command and a secure understanding of the examinable material. Scripts will contain substantially correct solutions to most of the quantitative parts of a question, showing a good grasp of mathematical skills. For the essay and questions of an essay nature, first class marks will be awarded for work which is excellent, both in range and in depth of knowledge and in the argument and analysis that it brings to bear.

Upper Second class marks, II.1

A candidate placed in the upper second class will be able to demonstrate a good command and some understanding of the examinable material. Scripts will contain solutions to most of the quantitative parts of a question, thereby demonstrating the basic skills involved. For the essay and questions of an essay nature, II.1 marks will be awarded for work that demonstrates knowledge, but which does not provide as impressive a display of understanding, argument and analysis as those in the first class.

Lower Second class marks, II.2

A candidate placed in the lower second class will be able to demonstrate some command of the examinable material but with limited understanding. Candidates should demonstrate the ability to make good attempts at the straightforward parts of questions but limited ability to tackle any of the more challenging topics. Answers to questions of a mathematical nature will show an indication of what is required, but fail to proceed sufficiently far into the later parts to demonstrate the skills involved. Essays in this class may often read like prepared material rote learnt for the occasion and fail to be impressive in the range of relevant knowledge and depth of understanding, being superficial in scope or lacking clarity of structure.

Third class mark

A candidate placed in the third class will be able to demonstrate some knowledge, but have a poor command of the skills expected and very limited understanding of the examinable material. Essays in this class may be unduly brief, lacking in examples or failing to adhere to the rubric, by, for example, answering intelligently, but on material unrelated to the question, or containing some relevant material presented without clear structure or reasoned explanation.

Ordinary/Fail

A fail mark will be given when a candidate demonstrates little or no knowledge of the material and little or no ability to begin to tackle questions of a mathematical nature. Essays in this class will demonstrate unsatisfactory command of material through a lack of knowledge and an inability to demonstrate any appreciable understanding. It is likely that such answers will be very brief and incomplete, or rambling and irrelevant.

Exam Papers accessed via web page (earlier papers available on request)

http://www.ast.cam.ac.uk/students/undergrad/part_ii/exam.papers

Formulae sheet (provided for all examinations)
https://www.ast.cam.ac.uk/sites/default/files/Formula.Booklet_2020.pdf

http://www.maths.cam.ac.uk/undergrad/pastpapers for past examination questions on Principles of Quantum Mechanics for 2011 or earlier.

Transferable Skills

All students in the University are encouraged to engage in personal development planning. The astrophysics courses are designed to provide all students with opportunities to develop a wide range of transferable skills. The University also offers plenty of opportunities to acquire skills outside the curriculum particularly in College-based activities and in numerous specialist interest clubs and societies.

The Institute of Astronomy has identified the following set of skills and attributes which all undergraduates can reasonably expect to acquire during their university career. These skills enhance students' academic performance, can be used beyond university, and are valued by employers.

This note sets out the ways in which transferable skills are acquired through the teaching programme offered by the Institute. The Part II and Part III Astrophysics courses overlap with courses provided by the Departments of Physics and Applied Mathematics and Theoretical Physics and so the transferable skills policy statements of those departments are also relevant.

Intellectual skills

The most important intellectual skills which our students learn are abilities at quantitative and qualitative reasoning in the exact physical sciences and the application of this understanding to problem-solving.
Examples include: development of models of phenomena; mathematical analysis of models; appropriate approximation; statistical analysis. These skills are developed in: Department: through lectures, examples classes, seminars, projects and examinations; College: supervisions involving discussion, reasoning, problem solving, and critical analysis.

Communication skills

All students develop their communication skills as part of the teaching and assessment programme. In Part II essays and Part III projects credit is given for the quality of the student's communication skills. The principal elements of the training involve:

Writing

Department: Guidance notes provided by the Department on the preparation and presentation of Part II essays. Individual guidance by supervisors of Part III research projects, encouraging a critical attitude and an innovative approach to problem solving.

College: Supervisions involving the discussion and written solution of problems.

Oral

Department: Oral presentations of project work in Part III (also including software presentation packages and visual aids).

College: Supervisions involving oral explanations and discussion with supervisors and other students.
Non- verbal (development of an argument using mathematical concepts or symbolic language):

Department: Computational projects, essays and examples sheets. College: Supervisions involving problem solving. Organisational and interpersonal skills.

Students develop self-discipline in the management of a complex work programme of lectures, supervisions, examples classes, projects, literature reviews and examinations with strict deadlines. Interpersonal skills and self-expression are developed through constant interaction with peers, supervisors, lecturers and working within a research group as part of a Part III project.

Department: Provision of a framework within which the students carry out their work programme with clear deadlines. Advice on organising the programme of work in the Course Guide.

College and University societies: Oversight of the students' programmes is maintained by Directors of Study and Tutors. Advice on organisation of the work programme through supervisions. Living, working and socialising in a diverse community; taking positions of responsibility.

Research skills

Students develop information-acquisition skills from the selection and use of appropriate text books to the sourcing and assimilation of scientific literature particularly for essays and projects.

Department: Development of all aspects of research skills involving the application of understanding of concepts to new problems. Use of library, electronic and Internet resources to supplement information given in lectures and supervisions; critical analysis of published papers in preparation for Part II essay; Part III research project. Appreciating how to access the experience and knowledge of expert scientists.

Numeracy and Computing

Success in astrophysics is dependent on a high level of numeracy and computing skills, all of which are highly transferable to other spheres.

Department: In earlier years of the Natural Sciences Tripos students will have followed courses in mathematics. All astrophysics courses contain mathematical elements. Lectures and examples classes are provided in mathematical methods and statistical astrophysics; daily use of mathematics and computational methods for study and problem solving; data analysis in essays and projects. CATAM courses are specifically focused on programming skills, many at a very advanced level.

College: Supervisions in all courses. Computing resources for the above; e-mail and Internet access. Word processing is used for all aspects of written communication.

Foreign Language Skills

Students have access to the University's Language Centre and extensive opportunities for self-teaching in foreign languages.

Appendix 1

NST Part II Astrophysics

Guide to Class Boundary Construction

1. The examiners mark the examination questions numerically with a quality mark α or β if a certain standard is reached. The examiners are free to choose this standard depending on the question but normally a numerical mark on part (i) of 5–7 is awarded a β while 8–10 is awarded an α. On part (ii) 10–14 is normally awarded two βs and 15–20 two αs.
Candidate's total numerical marks (awarded on examination questions and project work/essay) and quality marks (numbers of αs plus half the number of βs) are used to produce a plot of total marks versus quality marks. Also plotted as reference are the class boundaries for (at least) the previous two years.

2. The quality marks and total marks per candidate are compared to the previous two years to gain an insight into whether the examination is easier or more difficult. In the case that examinations are back to in-person exam hall conditions in the 2020/21 academic year, then the 2019/2020 Pt2 exam results attained under remote conditions will not be used for comparison. If the class lines for previous years indicate a very different result for the ensemble, then this suggests that the examination may have been too hard or too easy. The locations of the highest and lowest performing candidates can also give insight into the relative difficulty of the examination.

3. The dividing lines between firsts and upper-seconds, upper-seconds and lower-seconds and lower-seconds and thirds are adjusted in the light of these considerations. The dividing lines may be moved slightly upward or downward depending on whether the exam is judged harder or easier than in previous years. It is undesirable for the dividing lines to separate strongly clustered candidates on the total marks versus quality marks plot.

4. Candidates just below a boundary are usually invited for a viva, together with calibration candidates whose class is not in doubt.

5. The examiners now consider scenarios in which any candidate may have been disadvantaged by typographical errors or other issues arising in the examination. If necessary the locations of candidates including and excluding marks from the disputed question, or even papers, are considered and the examiners look to see if any candidate moves across class boundaries. The candidates' identities are then revealed.

6. The vivas are conducted by the Senior Examiner and the External Examiner. Candidates receive a viva mark, in addition to their regular marks. If the viva mark is sufficiently good, then a candidate may go up a class. Candidates cannot be disadvantaged by the viva.

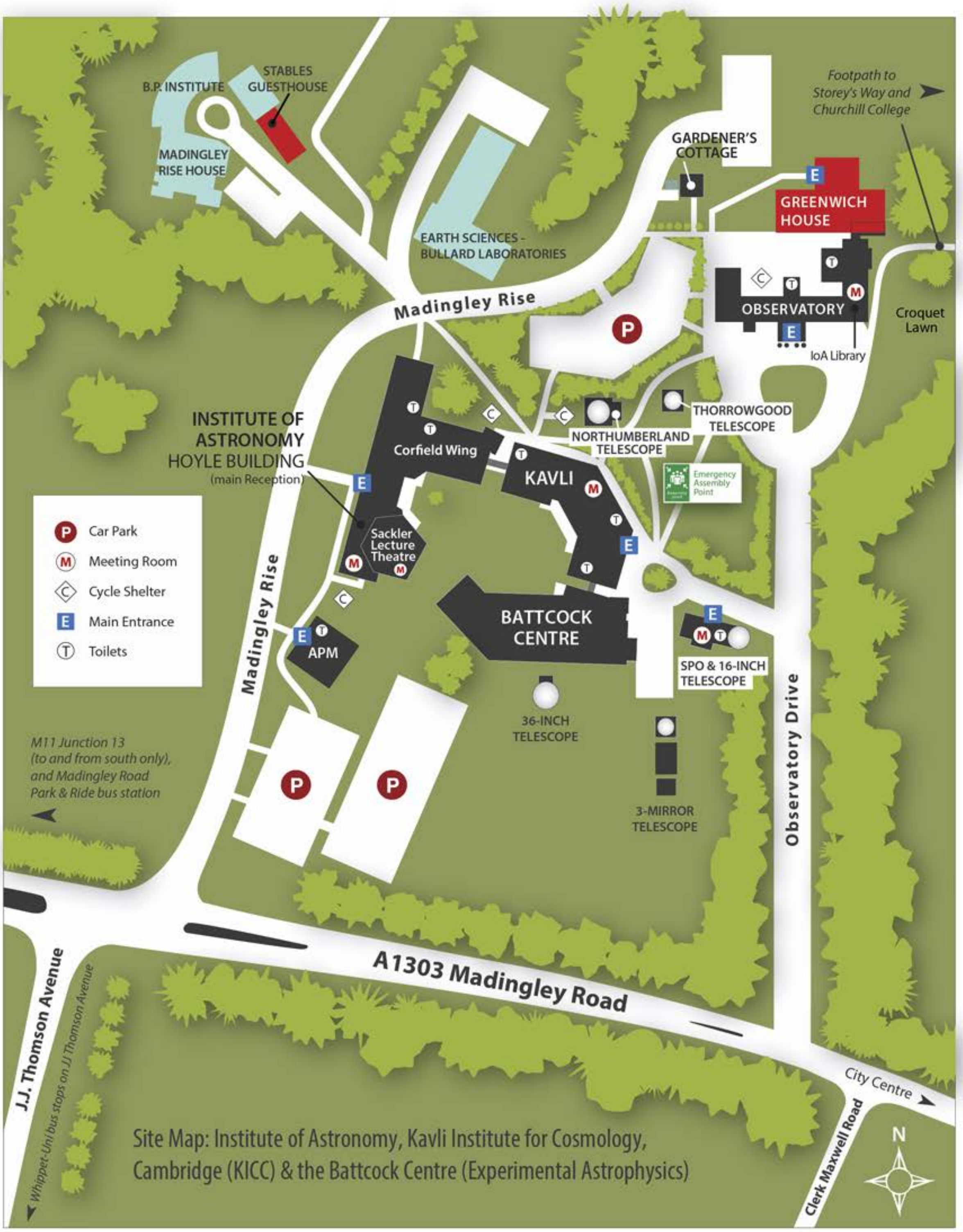
7. NST marks are assigned based on distances of the (total mark, quality mark) points from the class boundaries, with the first/upper-second boundary corresponding to an NST mark of 70, the upper-second/lower-second boundary to a mark of 60, the lower-second/third boundary to a mark of 50

and the third/fail boundary to a mark of 40.

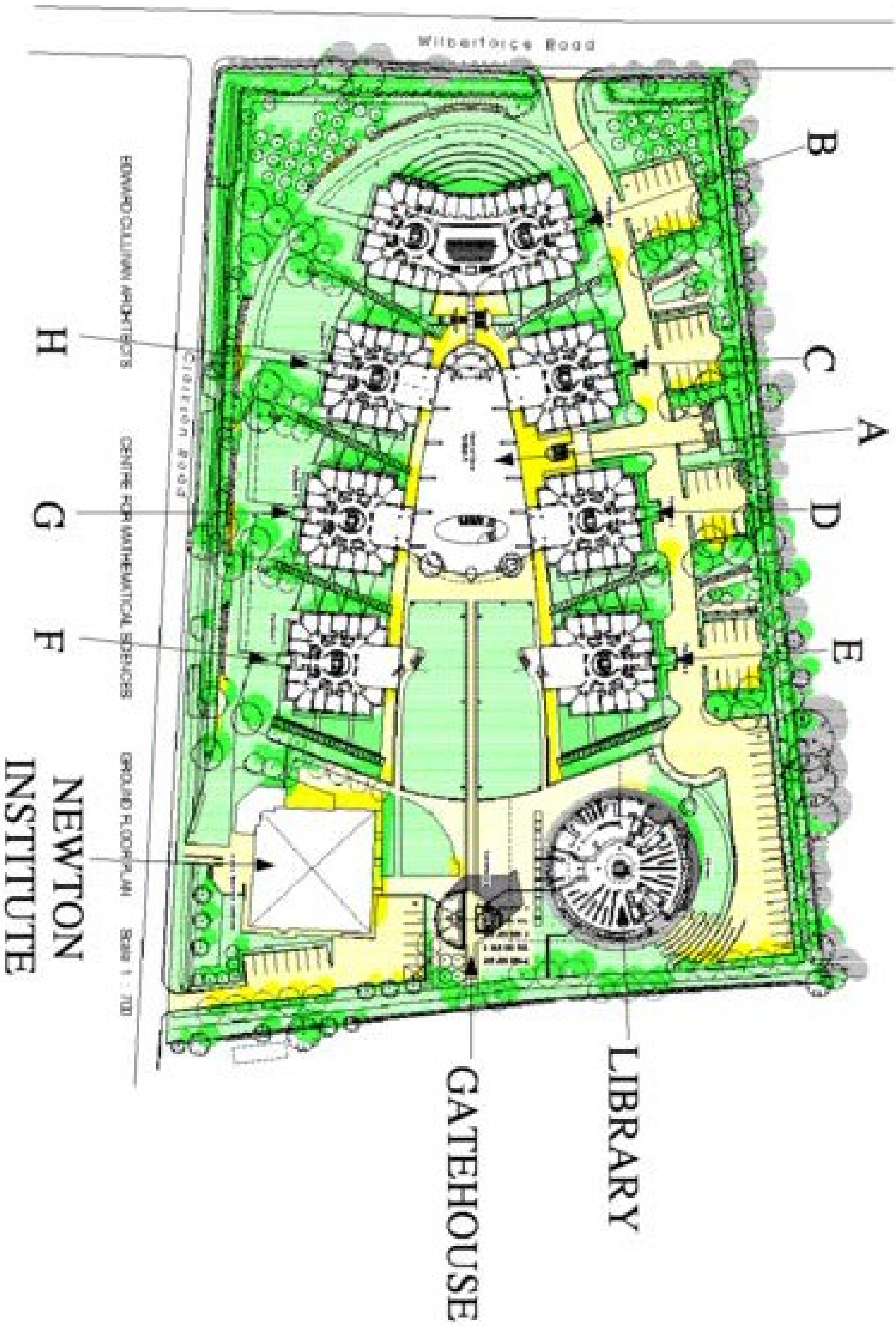
8. Final NST Marks and Classes having been agreed, the Class List is produced and signed by the examiners.

Mark Wyatt (Senior Examiner 2017)
Oliver Shorttle (Senior Examiner 2021)

Welcome to the Institute of Astronomy



© IoA 2016 - MAP NOT TO SCALE


Wilberforce Road
Clarkson Road
EDWARD CULLINAN ARCHITECTS
CENTRE FOR MATHEMATICAL SCIENCES
GROUND FLOORPLAN
B
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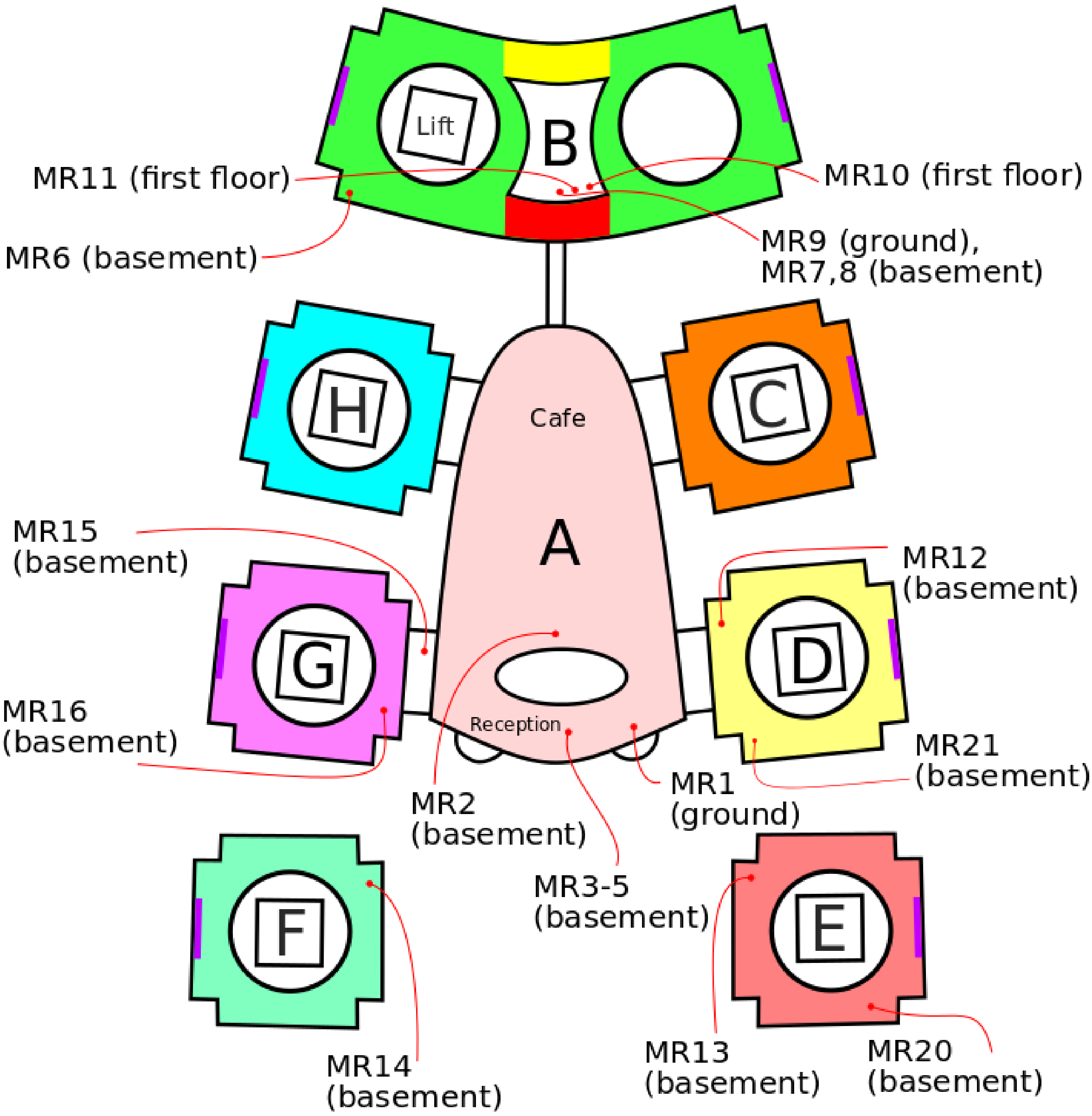
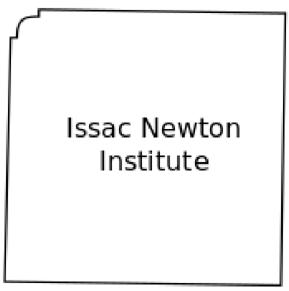
NEWTON INSTITUTE
GATEHOUSE
LIBRARY



Access to MR1-5, MR13-16
is via reception in Pavilion A;
disabled access is via lift
in Pavilion D.

All pavilions except A
have one lift each,
marked above with
squares.



UNIVERSITY OF CAMBRIDGE

INSTITUTE OF ASTRONOMY

Safety Manual

Action if you discover a fire

Operate alarm
using nearest break-glass unit

Call Fire Brigade: dial 1999

Tackle fire with hand-held extinguishers
if safe to do so without personal risk
or
Evacuate building by nearest exit

Do not stop to collect belongings
Do not re-enter building

Action when fire alarm sounds

Leave by nearest available exit
Assemble on Thorrowgood Lawn
(between Observatory and SPO buildings)

University Security Control Centre

24 hour number 31818
Emergency number 101

Accidents

For Ambulance dial 1999

First Aiders

Cormac O'Connell 07801707058 or 37505
Monica Gamboa 37548
Mark Hum (Library Office) 37537
Debbie Peterson (H6) 66643

Updated: September 2020