Institute of Astronomy
University of Cambridge

Natural Sciences Tripos

Part II Astrophysics

COURSE GUIDE
2011-2012

http://www.ast.cam.ac.uk/sites/default/files/PartII_CourseGuide.pdf

Natural Sciences Tripos - Part II Astrophysics 2011 - 2012

Introduction

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 2011 may either graduate in 2012 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 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 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 - Theory of 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, PhysicalCosmology, Stellar Dynamics and Structure of Galaxies and Structure and Evolution of Stars.

Five lecture courses are unique to Astrophysics. The rest are courses shared with Part II Mathematics or Physics. In the Michaelmas Term one of the courses (Topics in Contemporary Astrophysics) plays the dual role of introducing students to a range of exciting topics in contemporary astrophysics and developing abilities in physical reasoning and order of magnitude estimates in an astronomical context. The other courses are foundation courses in Relativity (in the Physics Department), Quantum Mechanics (in the Maths Department) and Physical Cosmology. In the Lent Term there are four courses, Astrophysical Fluid Dynamics, Structure and Evolution of Stars, Galactic Dynamics, and Statistical Physics (in the Maths Department). 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.

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.

Preparation for Part II

In order that all students are well equipped for the course, we require 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.

Lectures and Supervisions

Timetable

Michaelmas 2011	Lent 2012
All lectures will be delivered in the Sackler Lecture Theatre except [M] which will be held in the Centre for Mathematical Sciences meeting rooms (MR) and [P] in the Pippard Lecture Theatre at the Cavendish Laboratory (West Cambridge)	
Dr I R Parry Physical Cosmology, M. Th. 10 (12 lectures from M 24 October)	Dr I R Parry Physical Cosmology, M. Th. 12:15 (12 lectures from 19 January)
Dr M P Hobson Theory of Relativity, M. W. F 11 [P]	Dr M Wyatt Astrophysical Fluid Dynamics, M. W. F. 10
Prof A C Fabian and Prof G F Gilmore Topics in Astrophysics, M. W. F 12:15	Dr D Tong Statistical Physics. Tu. Th. S. 10 MR3 [M]
Prof. B Allanach Principles of Quantum Mechanics, Tu. Th. S. 11 MR2 [M]	Prof. C J Clarke Stellar Dynamics and Structure of Galaxies, Tu. F. 11:15, W. 12:15
Dr S. J. Cowley Computational Projects, M 10 October (one lecture only) 2-4.00, MR2 [M]	Prof. M Pettini Structure and Evolution of Stars, M. W. Th. 11:15

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.

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.

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.

Handouts

Course handouts and examples sheets are put in the pigeonholes below the Part II noticeboard outside the Course Secretary's office (H4). Please help yourself to whatever you do not get during the lectures.

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 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. During the Easter term there is a meeting so you can give feedback on the course overall.

Contacts

Course Coordinator:	Cathie Clarke	39087 Hoyle Rm 10	cclarke(at)ast.cam.ac.uk
CATAM advisor at IoA:	Paul Hewett	37507 Hoyle Rm 19	phewett(at)ast.cam.ac.uk
Course Secretary:	Judith Moss	37521 Hoyle Rm 4	jm(at)ast.cam.ac.uk
Teaching Committee Chair:	Christopher Tout	37502 Hoyle Rm 61	cat(at)ast.cam.ac.uk
IoA Director:	Paul Hewett	37507 Hoyle Rm 19	phewett(at)ast.cam.ac.uk
Director's Secretary:	Jeannette Gilbert	37538 Hoyle Rm 48	jyg(at)ast.cam.ac.uk
IoA Librarian:	Mark Hurn	37537 Obs Library Office	hurnm(at)ast.cam.ac.uk

The Course Secretary is in charge of 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 Cathie Clarke.

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 Notice board outside her office should also be checked frequently. In addition it is advisable to give her contact details for your Director of Studies.

Telescopes

There is no practical element to the course. However, students are encouraged to join the Cambridge University Astronomy Society through which they can gain access to various telescopes on the IoA site.

Schedules

The Schedules which follow are minimal for lecturing and maximal for examining. The topics starred in the Schedules will be lectured, but questions will not be set on them in examinations. The numbers which appear in brackets at the end of subsections or paragraphs indicate the approximate number of lectures likely to be devoted to the subsection or paragraph concerned. Books marked with † are particularly well suited to the course.

PRINCIPLES OF QUANTUM MECHANICS,

M*ichaelmas Term,* 24 Lectures

Dirac formalism

Bra and ket notation, operators and observables, probability amplitudes, expectation values, complete commuting sets of operators, unitary operators. Schrödinger equation, wave functions in position and momentum space. [3]

Time evolution operator, Schrödinger 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 $|jm\rangle$ 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. Reflections, 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]

Books

† E. Merzbacher *Quantum Mechanics*, 3rd edition. Wiley 1998 (£36.99 hardback).
† B.H. Bransden and C.J. Joachain *Quantum Mechanics*, 2nd edition. Pearson (£37.99 paperback).
J. Binney and D. Skinner *The Physics of Quantum Mechanics*. Cappella Archive, 3rd edition (£21.75)
P.A.M. Dirac *The Principles of Quantum Mechanics*. Oxford University Press 1967, reprinted 2003 (£24.99 paperback)
C.J. Isham *Lectures on Quantum Theory*: Mathematical and Structural Foundations. Imperial College Press 1995 (£14.00 paperback)

PHYSICAL COSMOLOGY,

***Michaelmas and Lent Terms* – 12 Lectures each**

The course is intended to provide a sound physical foundation to modern cosmology and the formation and evolution of the Universe. The Lecturer will introduce the principles of geometrical and astrophysical cosmology and will emphasise the direct confrontation of observational data with contemporary theories.

Standard cosmological model. Cosmological principle, role of galaxies and microwave background in the standard model, Hubble expansion, brief introduction to modern cosmology. [3]

Relativistic cosmology. Curvature, Robertson-Walker metric, Friedmann models and cosmological parameters including Λ, redshift, particle horizon. [5]

Observational tests. Olbers' paradox, source counts, Hubble constant and deceleration, luminosity and angular diameter vs. redshift, angular power spectra. [2]

Thermal history. Hot big bang, thermodynamics of the early Universe, cosmic inflation, primordial nucleosynthesis, relic neutrinos, matter and radiation dominated-eras, recombination and the microwave background spectrum. [6]

Growth of structure. Gravitational instability theory, linear and non-linear (spherical) collapse, effect of Λ on late-time growth of structure, CMB anisotropies, variants of dark matter. [4]

Observational probes of structure. Galaxy surveys and weak gravitational lensing, primeval galaxies, quasars and the intergalactic medium, WMAP, the Sunyaev-Zeldovich effect, baryonic acoustic oscillations. [3]

Recent developments and controversies [1]

Books

† Coles, P. & Lucchin, F. *Cosmology, The Origin and Evolution of Cosmic Structure* (Wiley) 2nd Edition (2002).
† Liddle, A. *An Introduction to Modern Cosmology*, (Wiley) 2nd edition 2003.
Peebles, P.J.E. *Principles of Physical Cosmology* (Princeton) 1993.
Peacock, J.A. *Cosmological Physics* (CUP) 1998.
Kolb, E.W. & Turner, M.S. *Early Universe* (Addison-Wesley) 1994.

RELATIVITY, *Michaelmas Term*, 24 Lectures

Handouts and examples papers for this course are available from the Department of Physics Teaching Information System.

Foundations of special relativity: Inertial frames, spacetime geometry, Lorentz transformations, spacetime diagrams, 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, instrinsic and extrinsic geometry, the metric tensor, lengths areas and volumes, local Cartesian coordinates, tangent spaces, pseudo-Riemannian geometry, scalar, vector and tensor fields, basis vectors, raised and lowered indices, tangent vectors, the affine connection, covariant differentiation, intrinsic derivative, parallel transport, geodesics.

Minkowski spacetime 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, accelerating observers.

Electromagnetism the electromagnetic force, the 4-current density, the electromagnetic field equations, the electromagnetic field tensor, the Lorentz gauge, electric and magnetic fields, invariants, electromagnetism in arbitrary coordinates.

The equivalence principle and spacetime curvature: Newtonian gravity, the equivalence principle, gravity as spacetime curvature, local inertial coordinates, observers in a curved spacetime, weak gravitational fields, intrinsic curvature, the curvature tensor, the Ricci tensor, parallel transport, geodesic deviation, tidal forces, minimal coupling procedure.

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

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, radar echoes, accretion discs around compact objects, gyroscope precession.

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

****Kerr spacetime**: the general stationary axisymmetric metric, the dragging of inertial frames, stationary limit surfaces, event horizons, the Kerr metric, structure of a rotating black hole, trajectories of massive particles and photons, Penrose process.**

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

Topics in italics might be omitted.

Books

General relativity: an introduction for physicists, Hobson M P, Efstathiou G P and Lasenby A N (CUP 2005). This covers all parts of the course.

Relativity: special, general and cosmological, Rindler W (OUP 2001). Good for the concepts and methods. Provides a lot of physical and geometrical insight.

Introducing Einstein's Relativity, d'Inverno R (OUP 1992). Provides a clear description covering most of the gravitation course material.

Gravity: an introduction to Einstein's general relativity, Hartle J B (Addison Wesley 2003). A clear introduction that does not rely too much on tensor methods.

Spacetime and geometry, Carroll S M (Addison Wesley 2004). A very thorough, yet highly readable, introduction to general relativity and the associated mathematics

General theory of relativity, Dirac P A M (yes, that Dirac...!) (Princeton University Press 1996). A short and well-argued account of the mathematical and physical basis of general relativity. Probably only useful once you already understand the subject.

TOPICS IN ASTROPHYSICS, ***Michaelmas Term,*** **24 Lectures**

- Stars and Stellar Evolution
- Compact Objects (WD, NS, BH) I & II
- Supernovae, pulsars, gravitational waves I & II
- Accretion
- X-ray binaries
- Active Galactic Nuclei I & II
- Things with jets & gamma-ray bursts
- Gravitational lensing
- Clusters of galaxies
- How science works/Basics/Dimensional reasoning
- Radiation mechanisms, and particle messengers
- Dark Matter
- Distances, Dark Energy, and why they matter
- Galaxies and their evolution
- Formation and evolution of the chemical elements
- Our solar system, and others

Books

† Carroll, B.W. & Ostlie, D.A. An Introduction to Modern Astrophysics (Addison-Wesley) 1996.

ASTROPHYSICAL FLUID DYNAMICS, ***Lent Term*****, 24 Lectures**

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 white dwarfs and neutron stars (supported by electron and neutron degeneracy pressure respectively) as well as the orbiting discs of gas and dust which feed black holes.

Introduction. The concept of a fluid, density and velocity. Kinematics: steady and unsteady flows, streamlines and particle paths; conservation of mass. Derivative following the fluid motion. [2]

Dynamics. Pressure. (Inviscid) momentum equation for a fluid under gravity, application to force of jet on a wall, momentum equation in conservative form, role of $\rho u_i u_k$ Poisson's equation for the gravitational potential and its derivation. The Virial Theorem. [3]

Simple steady states. Simple (barotropic) relation between pressure and density, physical examples. Hydrostatic atmosphere under uniform gravity; self-gravitating isothermal slab and its relevance to galactic discs; self-gravitating polytropes as simple models of stars, mass-radius relation. [3]

Energy. (entropy) equation with simple cooling law. [1]

Sound waves. Sound speed (adiabatic and isothermal). Description of why shocks occur. Rankine-Hugoniot conditions. 1-D shock tube, 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. Rayleigh-Taylor instability, Schwarzschild criterion; Thermal instability, Field criterion; statement of Kelvin-Helmholtz instability, Jeans instability. [3]

Viscous flows. Linear and circular shear flows. Accretion discs. [2]

Magnetohydrodynamics. The ideal MHD equations (**E** +**v**   **B** = 0). Alfven waves. [3]

Books

Acheson, D. *Elementary Fluid Dynamics* Oxford University Press (1994)
Batchelor, G.K. *An Introduction to Fluid Dynamics*, Cambridge University Press (1991)
Clarke, C.J. & Carswell, R.F. *Principles of Astrophysical Fluid Dynamics*, Cambridge University Press (2007)
Lamb, H. *Hydrodynamics*, Cambridge University Press (6th ed 1932, reprinted 1993)
Landau & Lifshitz, *Fluid Mechanics*, Pergamon Press (1987)
Lighthill, M.J. *An informal introduction to theoretical Fluid Mechanics* (Oxford University Press 1993)

STELLAR DYNAMICS AND STRUCTURE OF GALAXIES,
***Lent Term*, 24 Lectures**

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 $= -GM/(r-r_s)$. Vertical perturbations in axisymmetric potential; vertical oscillation frequency; nodal precession. [2]

Axisymmetric density distribution. General axisymmetric solution of ${}^2 = 0$. 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 (1987).
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)

STATISTICAL PHYSICS, ***Lent Term*****, 24 Lectures**

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. [4]

Classical and quantum gases. Density of states and the classical limit. Idea gas. Maxwell distribution. Equipartition of energy Diatomic gas. Planck distribution and black body radiation. Debye model of photons in solids. Interacting gases. Virial expansion. Van der Waals equation of state. Basic kinetic theory. [8]

Thermodynamics. Thermodynamic temperature scale. Applications of laws of thermodynamics. Thermodynamic potentials. Maxwell relations. Heat and work. [3]

Grand canonical ensemble. Variable particle number. Chemical potential. Example of interacting classical gas. Bose-Einstein and Fermi-Dirac distributions. Bose-Einstein condensation. Ideal Fermi gas. Pauli paramagnetism. [6]

Phase transitions. Critical point in gases. Symmetries. Order parameters. First and second order phase transitions. Ising model. Mean field theory.

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 paperback).
F. Reif *Fundamentals of Thermal and Statistical Physics.* McGraw-Hill 196
A. B. Pippard *Elements of Classical Thermodynamics*, Cambridge University Press, 1957
Huang *Introduction to Statistical Physics.* Taylor and Francis 2001.

STRUCTURE AND EVOLUTION OF STARS, ***Lent Term,*** **24 Lectures**

1. Basic Concepts

- Importance of stars in the broader context of modern astrophysics;
- The cycle of star formation/evolution; stellar populations in the Galaxy.
- Basic properties of stars: mass, temperature, luminosity, gravity, chemical composition, age.
- Photometry and colours; spectra and spectral lines.
- The Hertzsprung-Russell Diagram; spectral classification of stars.

2. **Measurements of Stellar Properties,** I

- Distance: parallax, apparent and absolute magnitudes
- Mass: binary stars
- Temperature: blackbody radiation, Wien's Law
-

3. Stellar Physics I

- Timescales: dynamical, thermal, nuclear
- Energy generation: H and He burning; Si burning; r- & s- processes
- Degeneracy; Chandrasekar limit
- Energy transport: radiative and convective

4. Stellar Physics II

- Equations of stellar structure
- Hydrostatic equilibrium
- Virial theorem
- Pressure
- Opacity
- Stellar properties as a function of mass, homology

5. Stellar Evolution and the H-R diagram

- Pre-main sequence evolution, Hayashi and Henyey tracks
- Hydrogen and helium main sequences
- Post-main sequence evolution: massive stars, supernovae, neutron stars, black holes
- Post-main sequence evolution: low mass stars, planetary nebulae, white dwarfs, Type Ia SNae
- Initial mass function and its consequences

6. Measurements of Stellar Properties, II

- Spectral line opacity and broadening.
- Curve of growth, abundance analysis
- Spectral lines as temperature indicators
- Photospheric pressure
- Chemical analysis; the solar abundance scale; evolutionary changes
- Velocity fields in stellar photospheres; stellar winds

Books

†Prialnik, D. Introduction to the Theory of Stellar Structure and Evolution, Cambridge University Press (2000).
† Phillips, A.C. The Physics of Stars, Wiley, (1999).
Carroll, B.W. & Ostlie, D.A. An introduction to modern astrophysics Addison-Wesley (1996).
Tayler, R.J. The Stars: their structure and evolution, 2nd Edition Cambridge University Press (1994).
Gray, D.F.The Observation and Analysis of Stellar Photospheres 3rd edition CUP
LeBlanc, F., An Introduction to Stellar Astrophysics Wiley

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 in some limited area of endeavour that have not been completely solved. 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, 3 May]**. Late submissions must be submitted via your College Tutor with an accompanying letter of explanation from the Tutor. The length of the essay shall be not more than 5,000 words (exclusive of tables, figures, footnotes, appendices, and bibliography). The subject of the essay shall be chosen from a list of approved subjects announced by the Director of the Institute of Astronomy not later than the division of the Michaelmas Term **[9th November]**. Each candidate shall, not later than the end of Full Lent Term **[Friday, 16 March]** notify the Director of 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 www.admin.cam.ac.uk/univ/plagiarism/students/statement.html.

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 9 November] 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 (rather than as stated in CATAM section 2.1.1).

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

There is a CATAM helpline, catam(at)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 Monday, 10th October, 14:00-16:00, CMS, MR2. Further help is available from Professor Paul Hewett 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 (18th 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 the Course Secretary's office, 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.

For the examinations candidates will be permitted to use only the standard University calculator CASIO fx 115 (any version), CASIO fx 570 (any version), or CASIO fx991 (any version). Each such calculator must be marked in the approved fashion.

It is the responsibility of each student to equip themselves with a suitable calculator as described. A few spare calculators are provided in examination rooms but only to students whose own calculator has malfunctioned.

SALE OF STANDARD CALCULATORS

Standard University calculators, the CASIO fx 991ES marked in the approved fashion, will be on sale at the beginning of Full Michaelmas Term 2011 at approximately £12 each as follows:

- Board of Examinations Office (for any subject except Land Economy), 10 Peas Hill;
- Computer Laboratory, William Gates Building, from the Student Administrator (for the Computer Science Tripos and the M.Phil. Examination in Advanced Computer Science);
- Department of Chemistry, Part IA laboratory preparation room (for the Natural Sciences Tripos);

Students are strongly advised to purchase calculators at the beginning of Full Michaelmas Term at the centres named above.

Students already possessing a CASIO fx 115 (any version) or CASIO fx 570 and fx991(any version) will be able to have it marked appropriately at no cost at one of the above centres.

The CASIO fx 991ES is being withdrawn by CASIO. Whilst stocks are available the Board of Examinations will continue to sell these calculators to students. Once this model becomes unavailable, the CASIO fx 115ES PLUS will replace it. The price of these calculators will be £16.

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/offices/exams/students/special_11.pdf

<u>The form of the examination</u>

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 may be found here and the examiners' comments 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 marks

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.

General Information

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

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 outside the Course Secretary's office 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, a number of observatories and European groups offer places, e.g. Anglo-Australian Observatory, Australia, Lund Observatory, Sweden.

CALENDAR

Some dates may be subject to change – please check the online version for updates.

Date and Time	Subject	Venue / Information
MICHAELMAS TERM 2011		
OCTOBER		
Tu 4 October	Full MICHAELMAS term begins	
Tu 4 October 10:00	Introductory meeting with Course Coordinator and IoA CATAM advisor followed by tour of IoA	Please see map Sackler Lecture Theatre
10:45	Library Tour by Mark Hurn, IoA Librarian	Library, Observatory Building
Approx 11:15	Coffee	Hoyle Building Foyer
Th 6 October fm 10:15	Photographs	Note: meet in Hoyle Foyer (IoA) outside Sackler Lecture Theatre for photos
Th 6 October 11:00	Part II Astrophysics Lectures begin (see Lecture List) - *Principles of Quantum Mechanics (M)*, Ben Allanach	MR2, CMS
M 10 October, 10.00	2nd *Topics in Astrophysics* Lecture - G F Gilmore - for succeeding lectures by Profs. Fabian & Gilmore *et al.* please see special timetable.	Sackler Lecture Theatre
M 10 October, 14:00-16:00	*Computational Projects* - Dr S. J. Cowley -- one lecture,	MR2, CMS
During 2nd wk of MT	*Supervision arrangements* - list issued	
Tu 11 October	Submission of CATAM Part 1B projects (NST students)	Judith Moss Hoyle Rm 4
NOVEMBER		
Wed 2 November 2.00-3.00	All students: Part 1B CATAM project examples class, Paul Hewett	Observatory Meeting Room
BY 9 November	Essay Topics announced	Part II Notice board, copies issued to all students and sent by email
	Presentations of Essay Topics by potential essay advisers	Sackler Lecture Theatre
M 28 November, approx 13:15	Pizza Party	Hoyle Committee Room
DECEMBER		
W 1 December	Last day of Michaelmas Term lectures	
F 3 December	Full Michaelmas Term ends	
LENT TERM 2012		
JANUARY		
Tu 17 January	Full LENT Term begins	
Th 19 January	Lent term lectures begin - (See Lecture List)	
During 2nd wk of LT	*Supervision arrangements* - list issued	
FEBRUARY		
M 27 February	Last Physical Cosmology Lecture, I R Parry	Sackler Lecture Theatre

10:00		
MARCH		
W 14 March	Last day of Lent Term lectures	Sackler Lecture Theatre
F 16 March	Deadline for essay choice to be given to Course Secretary OR students should inform Course Secretary of their intention to submit computational projects (CATAM) by this date.	jm(at)ast.cam.ac.uk
F 16 March	Full Lent Term ends	
EASTER TERM 2012		
APRIL		
M 16 April	See CATAM News announcement re date for submission of electronic files and location for submission of projects.	CATAM News item and email.
Tu 24 April	Full EASTER Term begins	
MAY		
W 2 May 10.00-16:00	deadline for submission of CATAM projects. Students should inform the Course Secretary which ones they have attempted.	Location: Room EL.09 (CMS reception for directions) Obtain a declaration form from CMS reception; or here.
Th 3 May 09:00-17:00	deadline for submission of Essay	Course secretary's office, H4
Tu 15 May 10.30-11.00 (TBC)	Feedback Meeting with members of the Teaching Committee	Hoyle Committee Room
Examinations : Provisional dates		
JUNE		
M 4 June, 09:00-12:00	NST2AS Paper 1	Mill Lane Lecture Rooms TBC
W 6 June, 09:00-12:00	NST2AS Paper 2	Mill Lane Lecture Rooms TBC
Th 7 June, 13:30-16:30	NST2AS Paper 3	Mill Lane Lecture Rooms TBC
F 8 June, 09:00-12:00	NST2AS Paper 4	Mill Lane Lecture Rooms TBC
	Meeting for students intending to continue to Part III Maths in 2011/2012 -- Part III Astrophysics students 2011/2012 can attend e.g. to collect guide etc.	MR2, CMS
Th 14 June, 09:00 (all students must attend)	Photo and vivas (see Examination Notice)	meet in Hoyle Building
F 15 June, 16:30	Examination results announced at Senate House	
F 15 June	Full Easter Term ends	