Discussion

J.V. Feitzinger: *Can you comment on TV teaching of basic astronomy in India and what plans has your institution to do this?*

J.V. Narlikar: Our Institution will be located next to the Education Media Research Centre, which has well equipped TV studios. We plan to use EMRC facilities extensively for making astronomy programs for students and the general public.

AN ASTRONOMY DEGREE COURSE IN THE U.K.: SYLLABUS AND PRACTICAL WORK

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1. Introduction

What is the purpose of an astronomy degree? Why should students wish to take such a course? What will they do after graduation? In what way would such a course uniquely differ from a physics degree with a little astronomy tossed in? And given that we are called upon to provide such a course, what syllabus might we teach? These are some of the questions that occurred to me as I was preparing this paper.

One obstacle to giving clear answers is that the higher education systems of various countries differ greatly in structure. As one who was trained in one system (U.S.A.) and who teaches in another (U.K.), I am perhaps in a better position than most to appreciate the differences in approach, and to weigh the advantages and shortcomings of each system. But, as Shakespeare's Dogberry said, "Comparisons are odorous," and I do not propose to do this! What I describe refers to current practice in the university system of England and Wales, and I will use my own institution's long-standing astronomy degree as an example.

2. The Astronomy Degree

The course is a three-year honours degree Bachelor of Science. There is no "breadth" requirement for students to take courses in other subjects, in contrast to the usual practice in North American colleges and universities. Normally, students arrive at our front gates at age 18, having recently obtained good results in national "A-level" examinations in physics and mathematics, roughly equivalent to successful completion of the first year in typical North American universities. Students generally apply for their degree courses during the year preceding their university entrance. They are informed that a binding commitment is not required because, as a joint Department of Physics and Astronomy, we are able to permit unhindered internal transfers between the physics, the astronomy, and the joint astronomy/physics streams at various times in the first year with a minimum of paperwork. There is also a mathematics/astronomy degree course in which the teaching is shared equally by the two separate departments.

In the United Kingdom, a good B.Sc. honours degree in astronomy is sufficient qualification for applying to undertake a postgraduate Ph.D. research studentship in the subject without any further qualifying examinations. Effectively, we now have the answer to our first question; the degree we teach must provide sufficient training in physics, mathematics, and astronomy to permit an outstanding graduate to undertake an original research project, lasting three years (or perhaps four), that leads to an acceptable Ph.D. thesis. The three-year undergraduate course is, therefore, of necessity a rigorous and intensive one, in which the final year specialized options are taught at a level typically found in postgraduate courses in North America. However, one of our graduates could not be expected to have the extensive broad exposure provided by the usual extra year or two of study required in North American universities before advancement to Ph.D. candidacy.

But, we admit many more students to study astronomy than could (or should!) ever go on to do Ph.D. research or — far more difficult — eventually obtain employment as professional astronomers. So, why do so many students apply for the course? In the overwhelming majority of cases, their motivation is intellectual curiosity and a fascination with the subject. On their application forms, roughly one-third indicate an interest in an astronomy-related career, another third indicate an interest in occupations open to any graduate with a "numerate" science or engineering degree, while the other third indicate "undecided," perhaps the wisest answer a 17-year-old might give. Thus, most are realistic enough to understand that "professional astronomer" may be a career ideal, but that the road is long and the obstacles formidable. For these reasons, we must ensure that our astronomy syllabuses always stimulate and motivate the intellectual curiosity and best efforts of our students, while providing a sound basis in physics, mathematics, and practical skills useful in a wide variety of careers.

For about a third of our graduates, some form of further training follows the award of their honours degree. This may be a Ph.D. studentship, a taught M.Sc. course in a related subject like remote sensing or atmospheric physics, or (far too rarely!) training as a secondary school physics teacher. The great majority of the remainder successfully obtain positions open to physics or engineering graduates generally, because industrial employers and the Civil Service usually are aware of the strong physics and mathematics content of the astronomy degree, and normally treat it on essentially equal terms. A surprising number of our graduates enter careers in the financial institutions of the City of London; several have trained to be accountants.

3. The Syllabus

The astronomy degree course must necessarily involve a good deal of physics and mathematics, including nearly all the basic material involved in the introductory and intermediate years of a physics degree. The uniquely astronomical content of each of the first two years at University College London is only about 30 percent of the total lecture and practical material met by the student. In our astronomy/physics joint degree, this is reduced to about 20 per cent. It is the final year's specialized courses that slake most completely the students' thirst for astronomical material, because they may enroll entirely for courses in astronomy, although they are encouraged to take one or two physics lecture courses if they wish.

A very brief summary of the astronomy degree syllabus is given in Tables 1 and 2 for each of the first two years. These courses involve 32 lectures and 4 problem sessions. In addition, practical and laboratory courses (which are discussed in more detail in the next section of this paper) constitute one quarter of the workload in each of the first two years.

In their third (*i.e.*, final) year, astronomy degree students undertake an independent and substantial research project dealing with some aspect of astronomy or space science (for details, see McNally 1989). Formally, the project counts as one-quarter of the year's work. In addition, all astronomy degree students undertake an advanced observational and practical course at our University of London Observatory in the north London suburb of Mill Hill. The remaining five lecture courses (of 30 lectures each) may be selected from among the following courses: Planetary Geology, Planetary Atmospheres, Solar Physics, Interstellar Physics, Stellar Atmospheres, Stellar Structure and Evolution, High Energy Astrophysics, Extragalactic Astronomy and Cosmology, Observational Astronomy (a practical), and Mathematics for General Relativity. Most of these courses are taught at the same level as graduate-degree lecture courses in North American universities: for example, "Stellar Atmospheres" covers most of the material in the first half of Mihalas (1978) although the order, emphasis, and some of the treatments are different, while the observational discussions are brought up to date each year. Astronomy students may opt to enroll in one or two physics courses with their Tutor's permission: Physics of the Earth, Atomic and Molecular Physics, and Plasma Physics are the most popular of these.

One of the keys to the appeal and excitement of the astronomy degree course is that, with few exceptions, each of these courses is taught by an acknowledged expert who is actively doing research in the particular subject being taught. The students, who often find their second year to be hard going and rather too dry and mathematical, frequently tell us that they find their final year to be the most intellectually stirring and stimulating of all, largely because of the depth and immediacy of these courses.

Our astronomy and physics joint degree is generally similar to the astronomy degree in the first two years, except that only one astronomy lecture course is taken instead of two each year. Waves, optics, and electromagnetism receive more thorough treatment, as does nuclear physics. In the third year all options within the Department are available to these joint honours students, subject only to a minimum of two astronomy and two physics lecture courses. These students are free to do the Observatory practical course as an option and must also choose between the astronomy and physics projects. About half of them choose one or the other option; several choose both. Thus they have the freedom almost to emulate the astronomers, or very nearly to follow the straight physics course, according to their inclination and possible choice of career or postgraduate course.

4. Practical and Laboratory Work

The degrees taught in the Physics and Astronomy Department at University College London include components of practical and laboratory work of several types, and together with the project in the final year add up to 25 per cent or more of the required course units; for the astronomy degree, the total is nearly 30 percent because of the mandatory Observational Astronomy course.

Why this strong emphasis on practical and experimental work? Firstly, the College has a long tradition of experimental work in physics, and was the first to introduce systematic laboratory instruction in England (1866). We can inculcate formally subjects that we consider to be essential to a good general scientific education, such as statistical analysis of data, computer programming, electronics, and numerical methods. We feel that these subjects are best comprehended in a laboratory or observatory environment, where repeated applications of the principles learned are immediately possible. At the same time, we find that these courses allow us to explore those dimensions of a student's performance not measured by examinations, yet which may be even more relevant than examination grades when predicting future success in research, industry, or commerce.

The units in the first two years are not confined to doing set experiments. About 40 per cent of the workload in each year involves "minicourses." In the first year, all physics and astronomy students attend a series of lectures on elementary statistics and data analysis, and undertake a self-paced tutorial Fortran course, as part of their astronomy practical and physics laboratory training. They also spend one week of afternoons working in the student machine shops learning the rudiments of metal-working, and they attend a short engineering drawing course following their examinations. Second year students attend minicourses on electronics and numerical methods, and do associated experiments and computations.

5. First-Year Course

First year astronomy and astronomy/physics students attend at the University of London Observatory for twenty sessions of three hours, from October through March. On clear evenings, they have the use of an excellent 6 inch (15 cm) refractor and two 8 inch (20 cm) Celestron reflectors. The 6 inch telescope is a temporary substitute for an 8 inch refractor that is undergoing refurbishment in our shops. These telescopes can be used for a variety of visual observing sessions or for photography. Theodolites are used for experimental determination of latitude and longitude, and a coelostat and small solar spectrograph are available for solar spectroscopy experiments during clear afternoons. On cloudy evenings, they undertake more formal set experiments that draw on a wide variety of sources, such as the *Sky & Telescope* series of laboratory exercises, Culver's (1984) book of exercises, Kleczek's (1987) re-publication and extension of Minnaert's (1969) *Exercises in Astronomy*, and the Edinburgh Teaching Package (Tritton 1989). We also use several of our own "home-grown" experiments, often based on material obtained at the Observatory (see Dworetsky 1989 for an example).

Our approach to practical work is governed by the benefits we feel our students ought to derive from it. In recent years the teaching of physics in British state schools has been under severe pressure due to a shortage of qualified teachers. Although they usually come to us well-qualified theoretically, we find that an increasing proportion of our intake have had no experience of laboratory work as part of their school courses. This lack of experience is generally quite apparent in about 25 per cent of our students in the first few sessions.

All students are required to keep a laboratory notebook in which all experimental measurements, sketches, calculations, and notes are kept. This notebook is not ordinarily to be marked, although it is subject to inspection at any time in order to verify that the student has actually done the work presented, or if we encounter problems when marking a written-up experiment. It need not be neat — but it had better exis! Students jotting down readings or calculations on scraps of paper quickly learn that these are subject to confiscation. Lesson one: a scientist (or science student) always keeps a laboratory notebook.

The average astronomy degree student will complete, and present for detailed marking, about eight to twelve experiments during the course. These must be written up in detail in other notebooks, which are then marked and returned the following week. Students are given constructively critical comments on each write-up; these are intended to give guidance in order to improve subsequent presentations. A numerical mark is also given.

Aside from the formal minicourse work, there are several specific skills we attempt to foster. The most important of these skills is undoubtedly the writing of clear complete sentences and paragraphs in good formal English. The set experiments contain several "thought" questions which usually require short written answers or (occasionally) mathematical derivations of formulae (usually quite straightforward). From time to time some remarkably twisted syntax emerges from students; the proportion of students who commit frequent spelling errors is depressingly large. During the academic session, improvement is usually noted in the majority of cases, presumably as a direct result of the markers' detailed comments.

Accuracy of calculation is also a virtue to be encouraged, as is clear presentation of results by means of tables and graphs. An appreciation of significant figures and the need to quote an error (whether formal or estimated) is illustrated by the results in Table 3, which are students' calculations of the distance (about 10^4 pc) to the globular cluster M15, based on RR Lyr mean photographic magnitudes. Two students quoted this result accurate to 0.01 pc; three rounded to the nearest parsec; five more correctly rounded to the nearest 100 pc; but of the ten who attempted the experiment in 1987-88, *only one* quoted an estimated error! The absence of an error estimate for a measured quantity is invariably noted, and commented on, by the markers.

Table 3. Examples of Students' Expression of Significant Figures

Student Code	Distance (parsecs) to M15 (Estimated from RR Lyrs)
A	10500
B	10924
C	$1.03\text{x}10^4$
D	10597.42
E	11263.33
F	10600
G	10600±500
H[a]	9100
J[b]	10666
K	10375

[a] Low value due to arithmetic blunder.

[b] Also quoted as $3.5\text{x}10^4$ ly.

A graph is often an excellent way to communicate a considerable amount of complicated information clearly and quickly. The ability to impart information in this way is something we try to encourage at every opportunity. As a reader, how might you have reacted to six *superimposed* RR Lyr light curves, without individual data points, coded only by color? One student submitted a graph drawn exactly this way! Contrast such a confusing approach with another, in which six light curves are shown separately in six small plots, with observed data points clearly shown by circled dots and error bars.

The ability to draw a clear sketch can also be useful, especially in note-taking and in describing a complicated object or pointing out particular details or features. From time to time, students are asked to make drawings, either of objects viewed telescopically (*e.g.*, Jupiter or the moon) or images on photographs. In all cases, we try to impress upon students the need to note basic details such as the actual size of the original photographic image, or the angular size of a telescopic object (bifilar micrometers may be used for the latter purpose).

Students are trained in the use of a variety of expensive astronomical instruments and measuring machines. Considerable care must be taken to supervise their work both from the point of view of personal safety when working in darkness, and to protect the equipment from damage. We employ postgraduate student demonstrators for this purpose, who also act as markers for specific experiments. These marks are reviewed by the academic staff member in charge of the course.

The syllabus of set experiments is intended to complement and illustrate lecture material. For example, classification of galaxies is only very briefly discussed in lectures, but is covered in some depth by one of our set experiments. Familiarization with the more important astronomical charts, atlases, and catalogues is another task specifically assigned to the practical course, while positional astronomy is amplified by three experiments of graded difficulty: *Apparent Motions of Stars* (easy), *Determination of Photographic Stellar Coordinates* (a bit more difficult), and *Determination of Latitude and Longitude by Theodolite* (an observational and computational challenge). One of our locally-produced experiments, *Star Counts*, provides an opportunity to study an open cluster statistically, while a suitable extension of Minnaert's (1969)*Motion of the Hyades* experiment permits the student to construct a realistic color-magnitude diagram. (It is astounding how many students reverse the conventional absolute magnitude axis!) Another London experiment (Dworetsky 1989) helps to illustrate some of the underlying physics behind the classification of stellar spectra. There are also set experiments that involve the study of Schmidt telescope photographs from Palomar and the U.K. Schmidt in Australia (Tritton 1989); our students especially enjoy the study of Palomar prints of the Cygnus region, and the study of asteroid trails on a U.K. Schmidt photograph of the Virgo Cluster. In addition, every student in the course is introduced to photography and darkroom skills.

Several experiments require some calculations, which the students may wish to perform on a computer. We encourage this, provided that the effort involved in programming is not greater than that required if a pocket calculator is used instead!

6. Second-Year Course

The second-year course is completely based in the laboratories at University College. The set experiments for Practical Astrophysics are intended to complement the course work on atomic physics, and involve training in laboratory spectroscopy, photoelectric instruments, interferometry, and other optical equipment. Each student also undertakes a six-week project, that (optionally) may be undertaken at the Observatory, although usually these are laboratory-based. The educational goals are, otherwise, the same as those in the first year; *e.g.*, to keep careful notes of scientific work; to write up the results of an experiment in an organized, complete, clear manner; to present the results of calculations or measurements in clear tables and graphs; and to provide an adequate analysis of experimental errors.

7. Third-Year Course

The third-year course is an advanced course in observational astronomy. Each student attends one evening per week for twenty weeks. There is a strong emphasis on computing work and numerical techniques for data analysis and theoretical modeling. Students are trained on our 24 inch (60 cm) reflector in the use of a modern astronomical spectrograph (Dworetsky 1980) and in astronomical photoelectric photometry. Spectrographic experiments include MK spectral classification, stellar mass loss, measurement of radial velocity (including solar reduction), microdensitometry of stellar spectra, *e.g.*, Balmer line profiles, and nebular spectroscopy. Photometry of variable stars is sometimes undertaken, weather permitting, and photography using our 24 inch (60 cm) refracting telescope may lead to a determination of proper motion (by measuring an archive plate as well as a new plate) or lunar libration. There are also set experiments (all locally produced) on spectrophotometry of Seyfert galaxies, UV spectroscopy of the solar chromosphere, stellar rotation, abundance analysis of stellar spectra, Fourier transforms and convolutions, and the orbit of a spectroscopic binary, among others. One very ambitious student derived the orbit of an asteroid from his own observations and computer program.

The quality of the written reports is even more important in the final year course. At this level, the goal is to apply all the experience gained in the first two years, and to submit complete reports of the work done, based on the model of scientific papers.

8. Concluding Remarks

Our degree course is extremely challenging, and necessarily so. Examinations are important, and good results indicate high levels of ability, but our experience over many years has tended to indicate that a strong showing in practical and project work is generally a more reliable indicator of research potential than good examination results alone. Our ideal research student in astronomy has not only obtained good marks in theoretical subjects, but has consistently shown that his or her practical work has been carried out with originality, care, energy, and enthusiasm.

In my current capacity as Tutor to Astronomy Students, I am asked to provide a large number of references. It helps to be able to inform prospective employers of an individual's ability to write clear reports, to carry out a meticulous scientific investigation, or to write computer programs that work. We are also able to observe their ability to put in a strong, sustained effort under pressure, when they do their final year projects.

While there is no doubt about the value of, and need for, the well-presented lecture courses in mathematics, physics, and astronomy which make up the bulk of our degree, the strong practical element adds a vital extra dimension to the training and assessment of astronomy students which cannot be provided solely by lectures and examinations.

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Table 1. First-Year Lecture Course Structure for the Astronomy Degree.

First Semester

Mathematics for Physics & Astronomy

Vectors and vector differentiation. Velocity and acceleration. Revision of elementary functions. Partial differentiation. Complex numbers, Argand diagram. Review of integration. Line and surface integrals. First order separable differential equations. Second order linear D.E.'s. Vector calculus. Grad, div, curl, ∇ operator, Gauss's and Stokes's theorems.

Text: Boas (1983), Chapters 1-7.

Introductory Classical, Relativistic, and Quantum Mechanics

Review of Newton's laws and basic definitions. Equations of motion. Harmonic motion including damped, forced oscillators. Angular momentum, torques, equations of motion. Vectors in mechanics. Kepler's laws. Coriolis effect.

Special relativity: Einstein's postulates, Lorentz transformations, time dilation. Quantum theory. Historical background, Bohr model of H atom, Heisenberg, wave functions, quantum numbers, Pauli exclusion.

Text: Kleppner and Kolenkow (1978).

Table 1 (cont'd). First-Year Lecture Course Structure for the Astronomy Degree.

Foundations of Modern Astronomy

Observational techniques: outline of optical, UV, x-ray, IR, Radio astronomy. Stellar and Solar astronomy. Interstellar matter. The Galaxy. Extragalactic astronomy and cosmology.

Texts: Zeilik and Smith (1987), Chapters 8-24; *or* Roy and Clarke (1982), Chapters 2, 7-18.

Second Semester

Mathematics for Physics and Astronomy Students I

(Mathematics Department)

Algebra: finite groups, linear transformations, matrices, determinants. Analysis: sequences, series, functions of a real variable, further differential and integral calculus. Taylor series.

Electromagnetism, Waves, and Optics

Electric charges and currents. Conductors. Capacitance. Dielectrics. Magnetism. Lorentz force. Inductance. AC theory and circuits. Waves and vibrations, superposition, boundary conditions. Reflection, impedance.

Fourier analysis. Doppler effect; Dispersion. Wave description of electromagnetic radiation. Interference phenomena. Diffraction (Fraunhofer and Fresnel).

Classical and Solar System Astronomy

Spherical astronomy: trigonometry, coordinate systems, navigation. Time and calendars. Star positions. Orbits, Kepler's laws, Kepler's equation and solution. Tidal effects.

Planetary interiors. The Earth-moon system. Ages of rocks and meteorites. Planetary atmospheres. Planets: description, spacecraft results.

Texts: Green (1985), *or* Roy and Clarke (1988) part 2. Jones (1984); Zeilik and Smith (1987) part 1.

Table 2. Second-Year Lecture Course Structure for the Astronomy Degree.

First Semester

Mathematical Methods in Physics

Vector algebra, curvilinear coordinates. Partial differential equations. Ordinary differential equations. Laplace's equation. Wave equation. Spherical harmonics. Bessel functions. Matrices and applications.

Quantum Physics for Astronomy

One-dimensional Schoredinger equation. Wave functions. Solution of infinite square well. Step potential: examples of tunnelling. Finite square well. More formal quantum mechanics: eigenvalues, eigenfunctions, expectation values. Angular momentum. Central field problem. Solution of H atom. Perturbation theory, Zeeman effect. Atomic and molecular spectroscopy.

Level and scope similar to Leighton (1959), Chapters 2-9.

Electromagnetism and Thermodynamics for Astronomy

Electromagnetism: review. Maxwell's equations, EM waves, solutions. Statistical and radiation thermodynamics. Classical thermodynamics. Kinetic theory of gases.

Second Semester

Mathematics for Physics and Astronomy Students II
(Mathematics Department)

Functions of a complex variable. Linear vector spaces. Analytical dynamics. Hamilton's equations.

OPTIONAL COURSES (in lieu of Mathematics II)

(1) Earth Resources.
(2) Digital Circuits.
(3) Computer and Microprocessor Systems.

Stellar Astrophysics

Stellar interiors: Basic equations, approximate solutions, energy generation, stellar evolution. Astrophysical processes: absorption, scattering, emission, line broadening, opacity sources. Stellar atmospheres: radiative transfer, grey atmosphere, "simple" LTE line formation.

Techniques in Modern Astronomy

Information acquisition and analysis of data. Optical astronomy. UV, x-ray, gamma-ray, infra-red, radio techniques and detectors. Gravitational waves. Cosmic rays.

Discussion

J.-C. Pecker: *Do you introduce in the curriculum any practical teaching with respect to bibliographical retrieval — how to find one's way in a library, how to read textbooks and review papers towards more specialized information,* etc.*? I have often had a bad experience with this problem; and, consequently, I introduced in Nice, in 1965-69 (graduate school), a specialized practical training in using documentation tools of all kinds. This has been, unfortunately, discontinued.*

M.M. Dworetsky: All our students write an essay in the first year, for which the proper use of the library and the preparation of a formal bibliography are important. Bibliography and library research are also emphasized in the project.

L. Gouguenheim: *What percentage of your students become professional astronomers? And what happens to the others? Are these 3 years of education in astronomy useful for them?*

M.M. Dworetsky: About 20 per cent undertake Ph.D. research. Of these about two thirds complete a thesis, and usually find a postdoctoral position. Permanent positions are harder to obtain; many of our Ph.D.'s obtain posts abroad. The other graduates generally compete successfully for jobs in industry and commerce. Graduate unemployment is very low.

M.K. Hemenway: *How large are your classes?*

M.M. Dworetsky: The astronomy entry group is usually about fifteen students each year; the astronomy/physics group is usually larger; about twenty enter each year.

C.R. Chambliss: *Your comments on the inability of many students to deal properly with significant figures are most interesting. I have found this to be one of the most difficult subjects to get across to many students in my basic course.*

M.M. Dworetsky: One thing to note is that where students are criticized for using too many digits, they tend to over-react and use too few significant figures in subsequent calculations.

P.P. Saxena: *Do your students get teaching in spherical trigonometry and spherical astronomy when they pursue their studies for B.Sc. degrees in astronomy?*

M.M. Dworetsky: All students attend a short series of five lectures on spherical trigonometry and basic spherical astronomy as part of the practical course. There are further lectures on positional astronomy given in the Classical and Solar System Astronomy course (Table 1).