Steps toward new ways of teaching astronomy

L. M. Celnikier
Observatoire de Meudon, 92 Meudon, France
(Received 12 August 1977; accepted 18 March 1978)

In this paper, I submit that astronomy-astrophysics courses should be restructured, particularly since the subject is being increasingly opened to nonastronomers. Astronomy provides numerous examples in which one and the same concept is used in many different contexts (experimental techniques as well as theory): this pedagogically invaluable feature is generally lost in traditional courses and books which concentrate on modeling a particular object or class of objects using many different ideas simultaneously. Response from students to experimental courses of this nature has been most encouraging.

Elementary astronomy and astrophysics courses are becoming increasingly common in many universities in Europe as well as in the United States; I have myself taught such courses at the University of Paris (Université Pierre et Marie Curie) for a number of years. Such courses have stimulated the appearance of an enormous mass of astronomical literature aimed at the freshman to intermediate levels.

A glance at the programs and the literature offered to students leaves one rather surprised and discouraged: astronomy is being taught and presented today much as it was about 30 years ago. Of course, the technical means have changed: we have films, slides, beautiful photographs, glossy paper, . . ., but the content and the spirit of the presentation have changed remarkably little. Even the latest books are all depressingly similar: one sees the same drawings, the same photographs, the same ideas expressed in much the same way in practically every text on the market. I know of only one book which represents a real departure: it is *The Universe,"* by J. Kleczek—and it is much too brief.

Now, it is by no means clear that there is just one and only one way to teach astronomy; in this paper, I shall try to outline an alternative kind of approach.

What is the purpose of teaching an elementary astronomy course? The traditional answer is . . . to teach astronomy. From this answer has evolved the kind of program we all know so well: radiation, instrumentation (generally optical, but now with some mention of radio as a separate technique), the solar system (zoology and celestial mechanics), the sun (zoology), the stars (evolution), the galaxy (content of), galaxies (types), cosmology (origin and fate of the universe). Practically every author and teacher follows this structure, modifying the recipe by at most leaving out one or another ingredient; the only difference between a one semester and a multisemester course is often the depth with which each object is treated.

This scheme presents only one aspect of the subject. Astronomy is multidimensioned: one might picture it symbolically in Cartesian coordinates of which one "axis" represents "object under study," and the other axes might be "laws of physics," "observational techniques," etc. . . . (see Fig. 1).

Existing presentations typically select out a set of objects, ordered in some hierarchical way, and examine exhaustively what we know about each one in turn—in terms of our coordinate system, one moves from left to right along the "object" axis, stopping at each object and then branching along lines such as $A\,A'\,A''$.

Now, this certainly represents the way that astronomy has fragmented into a large number of narrow specialties, but it is neither necessarily the healthiest way to do research, nor is it by any means the only way to teach astronomy to students who will in all probability do something else afterwards.

In the final analysis, astronomy is a synthetic science: it is perhaps the only one in which we require (rightly or wrongly) that the laws of physics work everywhere in much the same way as they do "at home." However, this essential element is more often than not lost somewhere along the way in traditional presentations of the subject: for example, a student who has followed a course on stellar atmospheres rarely appreciates how much the basic physics resembles the phenomena in planetary atmospheres. Part of the fault lies in the jargon used—specialists do not talk the same language—but the fact that one teaches the two things separately and in separate courses does nothing to alleviate the problem. More generally, as physics courses become heavier, students are increasingly lost in a morass of apparently arbitrary recipes; they memorize them, but they are often incapable of applying the recipes outside the context in which they were first learned. It is precisely at this level that astronomy can play a major role: it can be used as a pedagogical tool to show how one and the same basic ingredients can be put together to create a wide variety of different dishes; however, to do this, one will have to stray from the traditional teaching program.

One interesting possibility is to divide astronomy into scientific topics—forces, movements, atoms, temperatures, quantum mechanics, structures, geometry and space, etc.—and to investigate how each topic is applied to different astronomical phenomena. Using Fig. 1 again, this corresponds to moving along the "laws of physics" axis, stopping at various places and then branching off along lines such as BB'.

A certain number of lecturers think that they are carrying out precisely this kind of program when they teach "astrophysics." I suspect that many are deluding themselves: they confuse "application of physics to astronomy" with "application of *simple* physics to *complex and varied astronomical phenomena*"—the words I have added change the entire emphasis. Astrophysics generally consists of beating to death some particular object with vast numbers of apparently arbitrarily chosen (but effective) physical laws. I propose the opposite—surrounding a particular physical phenomenon with many concrete astronomical examples. Moreover, when "astronomy" is being taught, even the illusion is no longer maintained—the physics is thrown in much as Macbeth's witches threw in "eye of

0002-9505/78/4610-0994$00.50

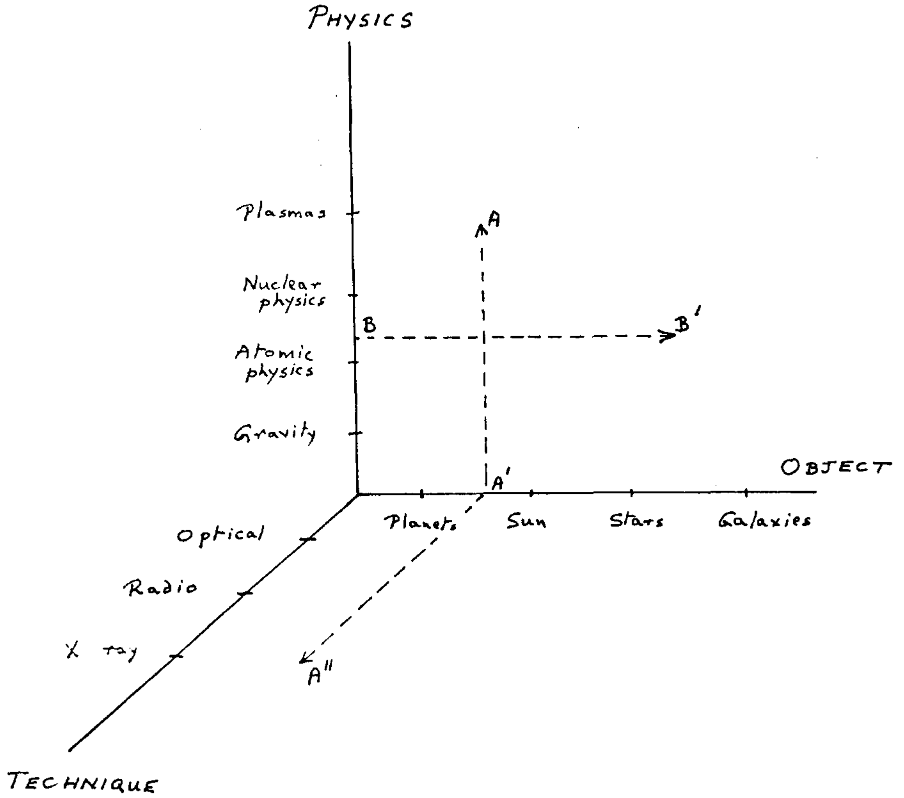

Fig. 1 Astronomy represented in a "Cartesian coordinate system," showing the synthetic nature of the science.

newt" and "toe of frog"; in the second half of the twentieth century, do we really need to maintain a distinction between "astronomy" and "astrophysics"?

Consider a concrete example—forces. One might begin with a discussion of the different forces we know, their laws, ranges, etc. One can then deduce at which hierarchical level each force should dominate (the answers will turn out to be only partly correct—in itself an illuminating result for the student). The course might then continue force by force.

(*i*) *Gravity.* Kepler's laws (solar system, multiple star systems, rotation curves of galaxies, . . .), the tides (Earth-moon system, slowing down of Earth, planetary satellites, deformation of close binary stars, synchronous orbits of binary stars, production of tails, bridges, etc., in multiple galaxy systems), escape velocity as an energy concept (escape velocity from a planet, expansion of the solar corona, mass of a star cluster, mass of an expanding universe, . . .). At each step, one will see that the basic physics is the same—only the details of the calculation change.

(*ii*) *Electromagnetic forces.* Interatomic binding forces (difference between a solid and a gas), what makes a planet a planet and a star a star (heights of mountains, limiting masses for stable solid bodies, energies necessary to disrupt atoms, . . .), resistance of matter against tidal forces of disruption (humans on the surface of the earth, pieces of ice in Saturn's rings, steel balls in orbit around compact stellar objects), comparison of gravitational plasmas and electromagnetic plasma (n-body effects, Jeans length and Debye length, . . .).

(*iii*) *Nuclear forces.* Impossibility of nuclear reactions within planets, stellar energy sources, resistance of nuclei against tidal forces of disruption in the neighborhood of an ultradense object, possibility of a "solid-state physics" based on internucleon binding forces (heights of "mountains" on pulsars, pulsar "geology," . . .), comparison of bulk properties of "nuclear" matter and ordinary matter (crystalline structure, conductivity, superfluidity, . . .).

This example can be elaborated at will. Other topics can be introduced in much the same way, always cutting across traditional boundaries, showing not only how a given law or definition applies to many different kinds of objects, but also (even especially) the underlying limitations of a particular method or principle.

Another interesting example is furnished by the notion of temperature. This is usually introduced separately for each object: each time the definition is different and apparently quite arbitrary (color temperature, brightness temperature, spin temperature, . . .). This is perhaps useful for doing physics, once one has understood the trick, but does little to help the student understand. An alternative approach might start from the basic problem—what is the meaning of temperature, and why are we interested in measuring it? Under what conditions is this parameter actually available . . . and is it a good parameter anyway? From this can develop a discussion of the way that radiation carries thermal information, and why this information might very well be distorted. Note that this part of the discussion is neither technical nor specialized: it is absolutely fundamental and should not be (although it often is) relegated to the tail-end of some other course. One might then continue with applications to specific objects: the moon, a planet, the sun, the stars, x-ray sources, neutral hydrogen, the universe, etc. In this way, the student comes to recognise that the basic physics of different parts of the electromagnetic spectrum is the same: moreover, by contrasting the results obtained using various spectral ranges (Jupiter, OH masers), one understands better such concepts as "nonthermal radiation," and how these phenomena enable us to extract new information about an object. Once again, introduced as a small part of a general analysis of some more or less obscure star, these ideas are often difficult to assimilate; presented in a single context and applied across the entire astronomical board they become much more transparent and familiar.

It is clear that a program based on some such "physics" subdivision requires very careful preparation, especially as specialists are often quite unaware of what goes on next door. Also, for such a presentation to succeed, the student must already be aware of some of the astronomical jargon in current usage. This is not as difficult as might appear at first sight: a historical survey of the concepts which will be analyzed later can serve as a convenient base. Here too there would seem to be room for change with respect to traditional "history of astronomy" courses. These latter pass inevitably from Thales to Newton, via Aristotle, Ptolemy, and Galileo; each model is generally introduced as a special "happening" with little reference to the scientific context of the period in question. It is much more illuminating and, as an introduction to the type of course suggested in this paper, much more useful, to insist on the interplay of different scientific ideas and to show how they evolved together. A useful starting point is a detailed synoptic table, with columns for astronomical discoveries, instruments, mathematical discoveries, technology, social evolution, etc., divided into convenient (not necessarily constant!) time intervals, showing what occured with what and when. The astronomical jargon will then emerge in a perfectly natural way, and one can pass to the physics topics with relatively little trouble.

One can in a similar way base a course on observing techniques. Beginning with a general survey of the electromagnetic spectrum, one can show how all techniques reduce to more or less similar principles—only the technical details change from wavelength range to wavelength range. One can then continue technique by technique, demonstrating how each one can be used to extract information about different astronomical objects. Again, the ultimate aim is a synthetic overview. Radioastronomical telescopes can be shown to be long-wavelength analogs of optical telescopes (how many students associate "radio lobe" with "Airy diffraction disc"?); grazing incidence x-ray mirrors can be shown to have the same relationship to normal incidence optical mirrors as these latter have to "wire mesh" radio mirrors. The entire philosophy of radioastronomical (and infrared) measurement can be related to perfectly humdrum industrial activities, such as the measurement of furnace temperature . . . an apparently specialized subject acquires relevance even for nonastronomers.

A secondary, but by no means negligible advantage accruing to this approach is the ability to integrate experimental work in a rather natural way. Many demonstrations and laboratory experiments are essentially physics based; when they are introduced in a traditional course, they often seem somewhat out of place, because they represent only a tiny part of the discussion which turns around the properties of a particular object. However, in our new presentation, they can often be the starting point.

So much for theory; how does this kind of approach work in practice?

I have so far seen it in full operation three times.

The first time I applied the basic ideas was at a summer school in Quebec, Canada, in 1977; the school was for high-school teachers wishing to teach astronomy to their students. I gave a course called "aspects of matter": beginning with a summary of the various forces we know, I pointed out in which astrophysical domains each one should dominate. This led naturally to a discussion on cohesion (gravitational, interatomic, nuclear) and disruption (tidal, ionizational, Saturn's rings, sizes of mountains), and energy generation. The next step was a "thought experiment": a bunch of grapes in a wine press, and a heater. What happens as one squeezes and heats? Using nothing more complicated than Heisenberg's uncertainty principle and the special relativistic formula for energy, I traced the various stages of compressibility and incompressibility, getting out a few critical numbers; this is very easy to do. The next thought experiment was on a cosmic scale—can one apply these results to anything other than a bunch of grapes? Here, still using nothing more complicated than Heisenberg's uncertainty principle and always applying the same physical reasoning, I extracted limiting masses for rocks, planets, stars, degenerate stars, neutron stars, and black holes; at each stage, the physical state of the medium was compared with the state of "laboratory matter" (gas, liquid, solid, crystalline, etc). Finally, I sketched how these states are "identified" in the universe around us, using simple radiation laws and the gravitational force laws I had already spoken about.

The second time, the audience was also a group of high-school teachers, and the occasion was a one-week astronomy school in France, in the summer of 1977. This time, the entire school was organized on the lines I have described. The program can be summarized as follows: (a) space through the ages (changing concepts of space and its measurement; this served as an introduction to much astronomical jargon), (b) forces in astronomy (gravitational → nuclear), (c) radiation and temperature, (d) movement (different kinds, its measurement, what one can learn from it), (e) why do the stars shine?

Each time, the response was highly gratifying: the teachers (basically physicists, but with a sprinkling of most other disciplines) told us what a relief it was to get away from the kind of mush which they are normally fed. Many of them, of course, knew each of the basic elements of the course; the novelty was the juxtaposition of certain, to them unrelated, ideas. Even those (mainly mathematicians) whose physics background was weak apparently found it helpful to see one and the same concept in various different contexts.

The response was sufficiently enthusiastic to justify expending further effort in the same direction.

I am currently teaching a two-semester astronomy course whose basic program is much the same as that of the summer school in France. An interesting addition is "time": its different manifestations, definition, measurement, etc. It is in this part of the course (rather than, as is usually done, in the context of "stars" or "radiation") that the elements of stellar evolution are introduced: the Hertzsprung-Russell diagram is presented as just another, more or less well understood, more or less well calibrated, "clock," related to nuclear "clocks" calibrated in the laboratory. As an experiment, I began the course with a traditional "recitation" along the "object" axis of Fig. 1. This took a long time and, in retrospect, compared with the other themes, seems somewhat tedious: next year, I shall sharply curtail it, or even eliminate it completely. The response to this course is most satisfactory. For the summer of 1978, I am projecting a school for teachers, whose general theme will be "physical principles of astronomical measurement." Here, we plan to show the fundamental identity (and the practical divergence) of observational techniques covering the entire spectrum.

Associated with the theoretical courses there will, of course, be practical instruction: apart from the kinds of things one inevitably does at this kind of gathering, I plan to set up a simple bolometer (a piece of brass with a laboratory thermometer inside it) to measure the solar constant, a reasonably sophisticated infrared bolometer (a Golay cell) to measure the temperature of the moon, and a decametric radio telescope to observe Jupiter. Once the basic material is available, each of these experiments can be set up by the participants at the school: in this way they can learn that amateur astronomy need not be just double-star hunting, but can be based on good simple physics. These are ideas that the teacher can take back to his school.

How far can one go with these kinds of programs? I do not really know. It is clear that any university student already knowing some physics can benefit greatly; I suspect (from my contact with mathematics students and teachers) that this is also true of students knowing no physics but wishing to learn it. It might appear that, since nonscientists cannot appreciate subtle resemblances in mathematical formulations, analogies will escape them: note, however, that analogies go much deeper than formulas and indeed, in practice, one is often led to a common formula as a result of apparent analogies (for example, the chromospheric heating phenomenon and the crack of a whip are really much the same thing). Why then exclude liberal arts students from this kind of discovery?

It seems to me that this structure is inherently more flexible than the traditional program. It can be used to introduce astronomy to students who might otherwise never have been exposed to it: a course for radio engineers, for example, can profitably talk about radio astronomical techniques, and how they can be applied to study the properties of the universe, while a course for meteorologists can include sections on the behavior of planetary atmospheres and interstellar clouds (for example, the Chapman theory for the ionosphere and the theory of HII regions are both based on one phenomenon—ionization equilibrium), on movements in stellar atmospheres, on radiation transfer in cosmic plasmas, etc. Without introducing very many radically new ideas, the student realises that his existing knowledge suffices to handle an enormous variety of new phenomena.

In these days, when an astronomy degree is a ticket for the dole queue (at least, in Europe), one can still teach the subject with a clear conscience, while producing people who are more "aware."