

Bringing the Universe into the Laboratory— Project CLEA: Contemporary Laboratory Exercises in Astronomy

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1. The Dilemma of the Introductory Astronomy Laboratory

Were we meeting a century ago to discuss the state of astronomy education, we might have noted that remarkable changes were taking place in our field. The discipline, then regarded as a branch of geometry or mechanics, concerned itself primarily with the determination of positions in the heavens and the mapping of places on the earth. But with the advent of spectroscopy and the construction of large telescopes, astronomy was beginning to probe the how and the why of the heavens as well as the where and when. It was, in short, transforming itself into astrophysics, the study of the physical nature of the universe.

A century ago, we would have called for a change in the things we teach; and in fact there was such a change. When we look at the astronomy of the succeeding century, the material we now offer to introductory astronomy students at most universities and colleges, we see only a vestige of the earlier preoccupation with place and time. Judging by most textbooks, and by the course syllabi I have seen, most of us devote only a small fraction of our courses to astronomical coordinate systems, timekeeping, geodesy, and celestial mechanics. When we teach the solar system, we teach comparative planetology. When we teach the stars, we teach about main sequence and giant branch, about hydrostatic equilibrium and neutron degeneracy, about pulsars and supernovae. When we discuss the universe at large, we teach about the physics of the early universe, the dynamics of galaxies, and the fundamentals of general relativistic cosmology. All these subjects draw heavily on a hundred years of work with large reflecting telescopes, sensitive imagers, photometers, and spectrographs, radio telescopes, spaceborne instruments, and even underground particle detectors.

But have astronomy laboratories kept pace with astronomy classes? Judging by published materials, our labs contain a disproportionately large fraction of 19th century astronomy, along with a smattering of exercises on astrophysics that rely on old data, the measurement of photographs, and the copying of tables and graphs (e.g. Hoff, Kelsey, and Neff, 1992; Bruck, 1990; Ferguson, 1990; Johnson and Canterna, 1987; Culver, 1984).

The reasons for this dissonance between curriculum and laboratory are quite understandable. Many of the results of modern astrophysics have been obtained using highly complex instrumentation, not easily operated by students. The availability of inexpensive CCD cameras and computerized telescopes has alleviated some, but not most of these problems. Many of the processes in astronomy take place at inconvenient times or over inconvenient time scales, and not simply because astronomy must be done at night—adolescent students, after all, are nocturnal creatures. Measuring the height of a lunar mountain requires a particular phase of the moon; observations of a binary eclipse or a stellar occultation must be precisely timed; pulsar variations demand split-second time resolution, while observing the proper motion of a star cluster demands a baseline measured in decades or centuries. None of these procedures fits comfortably into the measured routine of a weekly three-hour lab period, especially in temperate climates, where cloudy nights are frequent.

Yet if the limited options available for the astronomy laboratory are understandable, they are nevertheless regrettable. For many students astronomy is the first and only science course they will have in college, and it can powerfully shape their perceptions of what science is like, not to mention their understanding of the nature of the world around them. Studies have shown that students' understanding of science can be most firmly grounded on a base of concrete personal experience. (e.g. Hake, 1996; Thornton and Sokoloff, 1990; Rosenquist and McDermott, 1987).

Without a laboratory that complements the astrophysical material presented in textbooks, astronomy becomes a recitation of facts, many of them lacking in meaning to the first-time student. Students complain that laboratory exercises have little to do with the subject they are studying, or grumble that the exercises are make-work, involving little more than measuring photographs someone else has taken, copying numbers from tables to graph paper, and copying phrases from the textbook.

Hands-on experiences are common in experimental (as opposed to observational) sciences like physics, chemistry, and biology. In introductory chemistry, for instance, where the emphasis is on qualitative analysis, students learn quickly that many substances that appear as indistinguishable white powders at first glance differ profoundly in their densities, reactivities, and molecular structure. How many astronomy students come out of a course with the simple realization that most of the objects in astronomy are indistinguishable dots of light, and that, like the chemist, a major task of the astronomer is to tease out the fundamental structure of these objects using a standard array of analytic methods? How many astronomy students, rather, confuse the pretty diagrams of pulsars, black holes, and the spiral arms of the Milky Way with the faint objects astronomers actually see through the telescope.

How we know what we know is, I would maintain, as important as what we know. I do not intend to argue that the laboratory experience is the cure for all the ills of introductory astronomy education. I do believe, however, that the traditional introductory astronomy lab, with its emphasis on simple positional astronomy, elementary optics, and the clerk-like copying of data, lacks an important element of connectedness to the conceptual framework of modern astrophysics and to the methods of modern observational astronomy that impedes understanding and deprives students of the fun of discovery.

2. The Origins of Project CLEA

In recent years, a number of educators have noted that personal computers offer an powerful solution to the problem of the introductory astronomy laboratory. (e.g. Dukes, 1990; Marschall, 1995). Computers can provide simulations of astronomical observations that are extremely realistic, which is not surprising considering that computers, rather than telescopes, are the most widely used astronomical tools. Computers control optical and radio telescopes, interface with spacecraft, and are used in all steps of data analysis in astronomy. Large stores of digital images, spectra, and other data are available on CD-ROM and on the world-wide web.

A few astronomers, in the early days of the PC, began to develop computer simulation labs. Michael A. Seeds (Franklin and Marshall College), and Robert Dukes (College of Charleston), both developed telescope simulators in the 1980s, first on Apple IIs, and then on Macintoshes. Later, a group led by John D. Trasco (University of Maryland) created exercises that ran under early versions of Windows. Some astronomers began to use commercial planetarium programs, like *Voyager* for the Mac, and *Dance of the Planets* for the PC, to produce exercises in positional astronomy (Wooley, 1992).

In 1992, my colleagues (Michael Hayden and Dick Cooper) and I at Gettysburg College set out to develop a comprehensive set of computerized exercises. Realizing that new computers and new operating systems opened up wide possibilities for simulations, we obtained funding from the U.S. National Science Foundation which enabled us to hire a full-time programmer, Glenn Snyder (who has a Ph.D. in astronomy and 20 years experience with NASA science missions), and to establish Project CLEA (Contemporary Laboratory Experiences in Astronomy). Over the past 4 years, CLEA has developed 8 computerized laboratory exercises in astronomy which have met wide acceptance by the educational community. Distributed by mail and by the internet, CLEA materials are currently in use in all 50 states and more than 50 nations worldwide. (Marschall, 1995; White, 1996). Four CLEA exercises won a 1994 *Computers in Physics* award for best educational software.

3. Description of the CLEA Exercises

The CLEA exercises were designed with two principal goals in mind: to reinforce important concepts in astronomy, and to help students experience how astronomy is done. Each exercise consists of a software disk, a student manual, and a teachers guide with technical notes.

Several principles guide our design of classroom materials.

- Exercises are targeted at non-science students, who make up, by far, the majority in undergraduate introductory astronomy courses, as confirmed by our user surveys. While designed for standard 2 to 3 hour lab periods, CLEA programs have optional settings that make them useful for upper-class science majors, where appropriate, and they have been successfully used in classes from elementary school to senior college astronomy majors. (About 20% of our users are high-school students).

- Exercises are only developed for cases where expensive equipment, inconvenient time scales, or unavoidable complexity would make real observations impractical. Naked-eye stargazing is still the best way to learn the constellations; optics can be taught with real lenses and mirrors.

- Exercises have well-defined learning objectives and goals, which we state in our student manuals.

- Exercises are designed with the cognitive skills and technical sophistication of introductory astronomy students in mind. Some of these design considerations can be anticipated from previous studies in the literature (e.g. Arons, 1990). Others are taken into account by formal and informal feedback from our classes and by user surveys.

- Exercises avoid, as much as possible, rote copying and graphing. They emphasize how data is collected and analyzed, or demonstrate phenomena that can not be examined otherwise.

- Exercises make use of real digital data wherever possible. Our existing exercises use digital spectra, redshift, and radio source data from on-line or CD-ROM data archives.

- Exercises include instructive "real-life" features, such as detector noise, sky background, and weather interruptions, while avoiding complications that might distract from the principal learning objectives of the lab. Some exercises may include optional features that demonstrate the sociology as well as the logic of science, e.g. students must apply to use a large telescope—and may not be granted the time!

- Exercises are carefully designed for ease of use and uniformity. Extensive feedback from both students and faculty at other institutions makes the software easy-to-use and highly portable. This adds greatly to development time, but it insures that the materials we produce will have lasting value to a wide range of users.

- Exercises are independent of one another, and carefully documented so that instructors can pick and choose to fit individual needs. Since only about 20% of introductory astronomy courses are taught by professional astronomers (Michael Seeds, private communication, 1995), we make the exercises easy to install and use, but flexible enough for advanced users.

There are currently 8 CLEA exercises, covering a wide range of techniques and concepts from planetary astronomy to cosmology. The software runs under Windows, (Versions 3.0 and higher, including Windows 95 and NT), although one color Mac lab is available, and a number of rudimentary black and white Mac programs, lacking in many of the features of the Windows programs, are available as well. A brief description of each exercise follows:

The Revolution Of The Moons Of Jupiter

Purpose: *To illustrate the measurement of the mass of a planet using Kepler's third law.*

The software provides a view of Jupiter at four magnifications (actual Voyager images are used), along with a highly accurate ephemeris program that draws the four Galilean satellites in their proper positions relative to the planet at any time. Students make observations of Jupiter and its satellites at regular intervals over a period of several weeks and, by graphing the separation of each moon from Jupiter versus time, they measure the period and radius of each satellite's orbit. This is sufficient information to derive the mass of Jupiter. Students use the mouse cursor to identify the moons and to measure distances. A cloudy night feature provides some incompleteness to the data. Instructor-settable options set the percentage of "cloudy" days, suppress the automatic moon identification, and suppress the automatic calculation of distance from the planet. (Windows and color MAC)

The Rotation Of Mercury Using Doppler Radar

Purpose: *To illustrate the measurement of the rotation rate of a planet using the Doppler shift of a returning radar pulse.*

Students are given control of a simulated radar telescope. They point it toward Mercury and send off a narrow pulse of radio waves. During the time required for the pulse to go to Mercury and return (10 to 20 minutes, depending on the aspect of Mercury), the screen displays an animation showing the inner solar system and the position of the wave front of the pulse and its echo. The received echo, frequency versus intensity, is displayed for 5 time slices, which correspond to echoes from surface elements progressively further from the subradar point. By clicking the mouse cursor, students can measure the Doppler shift from the approaching and receding limbs of the planet, and from this determine (with appropriate geometrical corrections) the equatorial rotational velocity of Mercury. This, in turn, gives the period of rotation of the planet. Students use off-line calculators to reduce the data.

The software features on-line data recording, a printing option, and an on-line checker, which tells students if their calculations are "in the ballpark". Options include the ability to speed up the return pulse, reducing the waiting time. (Windows and b/w Mac)

The Flow Of Energy Out Of The Sun

Purpose: *To illustrate the statistical nature of radiative transfer in stellar interiors and stellar atmospheres. To show how photons diffuse in a random-walk pattern from the core of a star. To show how spectral lines are formed by random processes of absorption and re-emission in its atmosphere.*

This software contains several animated simulations that show photons in slow motion as they interact with matter and are redirected due to random processes of scattering, absorption, and re-emission. Students view the animations and measure the statistics of these processes. Each simulation can be run independently, or the entire set can be used as a full class exercise. One set of simulations deals with the scattering of photons in the interior of a star. The program demonstrates the random walk pattern of a photon generated in a simulated star as it makes its way to the surface. Students can vary the number of layers in the star to see how the number of interactions and the total length of the photon's journey vary in response. They can also shoot a pulse of up to a thousand photons all at once to see how the original spike diffuses out in an extended period of time.

Another set of simulations illustrates the transfer of radiation and the formation of spectral lines in the atmospheres of stars. In these programs, students can investigate the random nature of absorption processes, noting that photons whose energies correspond to electronic transitions of the atom seldom travel straight through a gas of those atoms. Students can experiment to see how many "line" photons make it through undeflected, as opposed to "continuum" photons, which travel straight through most of the time. They can experiment with samples of different gases. For a given gas, they can vary the photon energy, and by shooting photons through the gas and plotting how many make it through as a function of energy, they can learn how the statistics of a large number of photon interactions produce the dark absorption lines we see in the spectra of stars. (Windows and b/w Mac).

The Classification Of Stellar Spectra

Purpose: *To introduce students to digital spectra and to the process of classifying different spectra by the relative strengths of lines. To familiarize students with the sequence of spectral types. To teach how spectra are obtained. To show how the distance of a star can be estimated from its spectrum and a measurement of its apparent magnitude (spectroscopic parallax). To illustrate the need for large-aperture telescopes for the observation of faint objects.*

This exercise incorporates two separate but interrelated features: (1) a set of tools that enables students to view digital spectra and compare them with standard spectra from an atlas of representative types. (2) a simulated telescope that enables students to obtain spectra of unknown stars using a photon-counting spectrograph. In the first part of the exercise, students are asked to examine a number (typically 2 dozen) spectra of main-sequence stars and, by comparing them with a stored atlas of representative spectra, determine their spectral type. The software allows the digitized spectrum of the unknown to be displayed, flanked above and below by standard

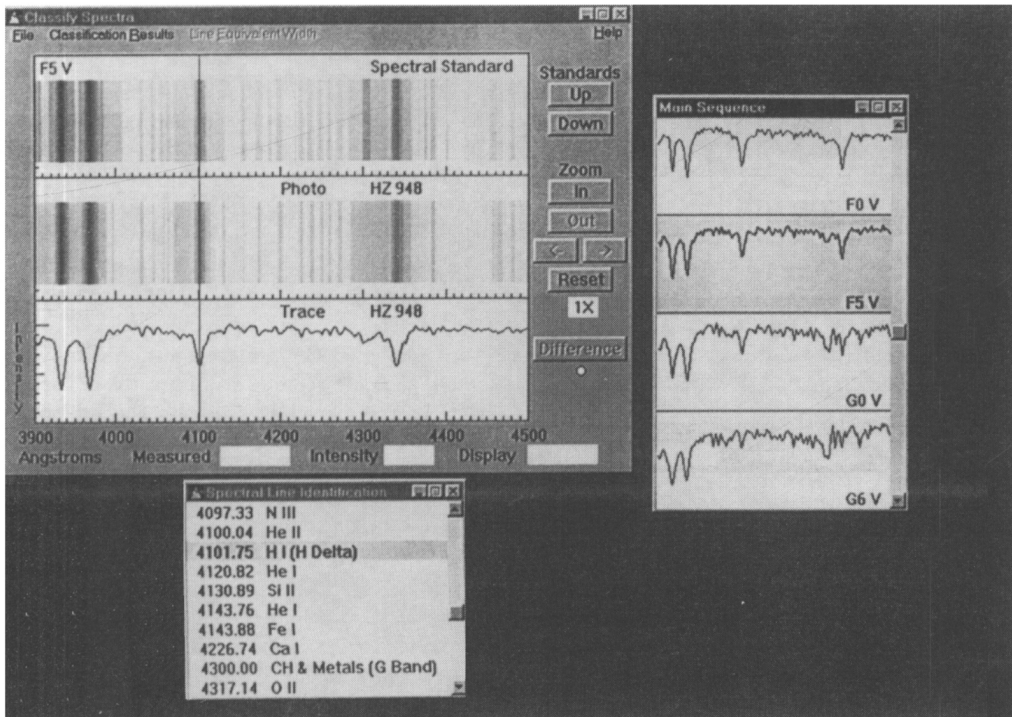


FIGURE 1. A screen from the *Classification of Stellar Spectra Exercise*.

star spectra. Zoom and pan features are provided, along with a measuring cursor. An atlas of spectral lines, coupled to the cursor, allows easy identification of prominent features. We provide nearly 200 spectra for use in this lab, including spectral standards for several luminosity classes as well as the main sequence.

Options include the ability to display the digital difference between an unknown and a standard spectrum, the ability to display the spectra both as graphs of wavelength versus intensity and as gray-scale photographs, and the ability to measure equivalent widths. Students can record their measurements on paper or disk files, import their data into spreadsheets, and run spreadsheets from the program shell. Since all the files read by the program are ASCII text files, the user can supply alternate digital spectra and additional line identifications.

In the second part of the exercise, students are given control of a simulated telescope. They can view a star field (a randomly generated field is supplied, but again, alternate fields can be specified using text files), center the spectrograph slit on an unknown star, and record spectra using a simulated photon-counting spectrograph. Spectra can take from several seconds to several hours to record sufficient signal-to-noise to identify faint features. The recorded spectra can be saved to disk and imported into the first part of the program where their spectra can be compared to standards. This information, along with the observed apparent magnitude of the star, can be used to derive a spectroscopic distance to the unknown star.

For faint stars, students may want to use a larger telescope. Three telescopes, with 0.4 meter, 1.0 meter, and 4 meter apertures, are available. To use the large telescopes, students must apply for time. Instructors can set the probability of success for using the larger telescopes (or make them open to unrestricted use), and the amount of time granted. A utility called GENSTAR is available from CLEA which generates customized files of star fields for use in this program (Windows only)

Photoelectric Photometry Of The Pleiades

Purpose: *To familiarize students with the technique of photoelectric filter photometry and*

counting statistics. To acquaint students with the use of a computer controlled telescope. To illustrate the use of equatorial coordinates for finding stars in a cluster. To introduce the use of H-R diagrams for analyzing the age and distance of clusters.

The software for this exercise puts students in control of a computer-controlled telescope with sidereal tracking (the "tracking" must be turned on or stars drift out of the field of view). Two fields of view are provided, a "finder" view of 2.5 degrees, and a magnified "instrument" field of view of 15 arc minutes. In the instrument mode, students see the outline of an aperture superimposed on the field. This marks the position of the entrance aperture of a photon-counting photometer. Controls are available to select one of three filters (U,B,V), to set the length of integrations and the number of integrations. Once these controls are set, students can take readings of the number of photons received from either a star in the aperture or from the sky (if no star is in the aperture).

In the configuration most suitable for introductory students, the program automatically calculates stellar magnitudes from the count rate, as long as a sky reading has been taken through a given filter sometime before the star is observed. For upper-class students the magnitude calculation can be suppressed and students can use the raw star and sky counts to calculate magnitudes. Information on the signal-to-noise ratio is also displayed after each series of integrations. A student guide supplied with the software describes how to use B and V photometry of cluster members to plot an Hertzsprung-Russell diagram of the Pleiades and to determine its distance.

We provide a database of stars in the Pleiades, but the data files for the stars are text files which can be modified by the user, so that data on any cluster can be substituted for the Pleiades, and exercises on the comparative ages of star clusters are possible. A utility called GENSTAR is available from CLEA which generates customized files of star fields for use in this program. (Windows and b/w Mac)

The Hubble-Redshift Distance Relation

Purpose: To illustrate how the velocities of galaxies are measured using a photon-counting spectrograph. To show how this information, along with estimates of galaxy distances (from their integrated apparent magnitudes) yields the classic Hubble redshift-distance relation. To determine the value of the Hubble parameter and the expansion age of the universe.

At the controls of a simulated telescope, students view distant clusters of galaxies and obtain their spectra with a photon counting spectrometer. The telescope offers two fields of view, a wide field view of 2.5 degrees, and a magnified field ("instrument view") of 15 arc-minutes. Stars are represented by realistic point spread functions scaled to magnitude, and galaxies by images from actual CCD frames. In the instrument mode, students can position the slit of a spectrograph on the galaxy and take spectra. The photon counting spectrograph simulates actual Poisson statistics and contains both a sky background and a galaxy spectrum. The relative contribution of the galaxy depends on how much "light" from the image is included in the slit, so that the highest signal-to-noise is obtained when the slit is positioned on the brightest part of the galaxy, just as with a real spectrograph. Students are advised to obtain spectra with signal-to-noise of about 10, so that they can see and measure the Ca H and K lines, which are used to determine the redshift of the galaxy.

Wavelengths can be measured using the mouse cursor, and recorded for further analysis. The spectrometer also records the integrated apparent V magnitude of the galaxy, which is used, along with an assumed absolute magnitude, to determine the distance of the galaxy. With this information for five or six galaxies at various distances, students can plot out a Hubble diagram, determine the Hubble parameter, and estimate the age of the universe.

A wide variety of instructor-settable options are available. Instructors can construct their own galaxy fields using GENSTAR, a utility supplied by CLEA, and can even install their own image files to represent galaxies. The integration time to reach a given signal-to-noise can be set to conform to the needs of the class and the speed of the computer. Even the value of the Hubble parameter can be specified by the instructor; the default is 75 km/sec/Mpc. (Windows and b/w Mac)

Radio Astronomy of Pulsars

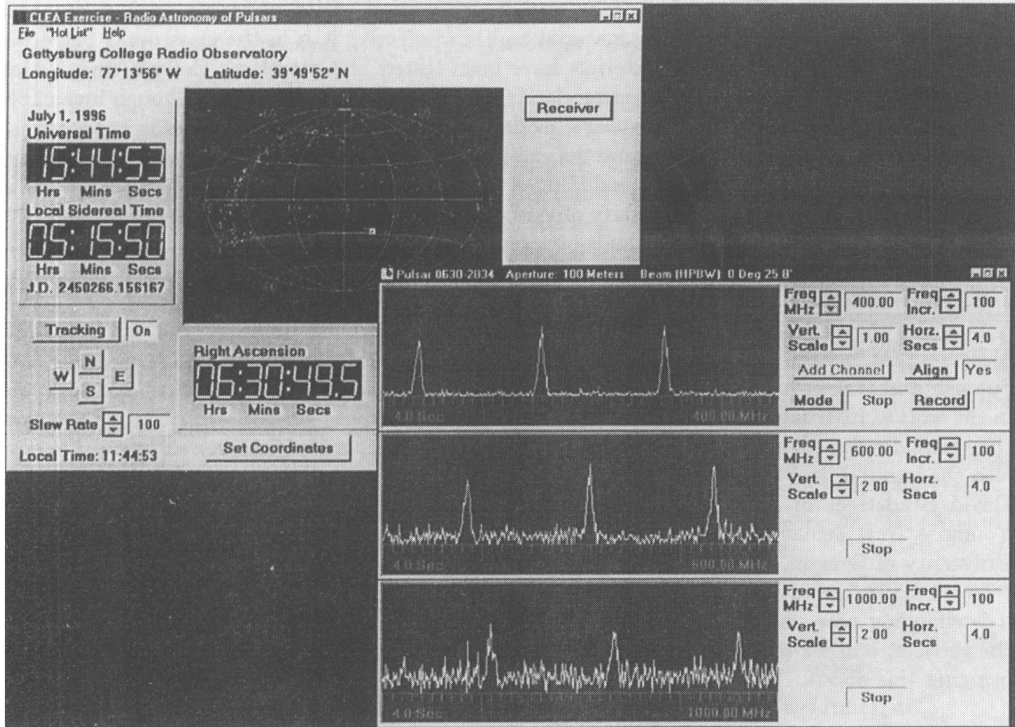


FIGURE 2. A screen from the Radio Astronomy of Pulsars lab currently under development.

Purpose: *To understand how radio telescopes are used to detect pulsars. To understand the fundamental observational characteristics of pulsars. To understand noise in observations. To understand how dispersion can be used to get a measure of the distance of a pulsar.*

This exercise, now in alpha-testing form, presents students with a radio telescope whose operating characteristics (beam width, receiver noise, steerability) can be set by the instructor. The telescope can be pointed at a source in the sky and the output of the receiver displayed on a graphic display (like a chart recorder or digital oscilloscope). The receiver can be tuned to a range of frequencies between 400 and 1400 Mhz, and additional independently tunable receivers can be added and displayed on the screen. Background and instrument noise are simulated along with noise intrinsic to the source. Data from each receiver can be saved for later analysis. Measurement windows, on which timing data can be recorded using the cursor, are provided as a default feature. Additional analysis tools (e.g. power spectra displays) can be called up at the instructor's discretion. Sound features are available to "listen" to the signal.

Students first view the signal and measure fundamental characteristics such as period and pulse width. They then view the signal at different frequencies and use the dispersion phase delay to estimate the distance of the pulsar. The radio telescope has optional features which can be used for additional labs, including a "transit" mode and a map of the galactic background noise. (Windows only).

4. Prospects for Future Development

Project CLEA's plans for the next two years include the development of at least 4 more exercises, selected from over a dozen outlines we have drawn up over the last few years. The list includes exercises on astrometry of asteroids, cepheid variables, radial velocity curves of binary stars, and a "capstone" lab where students identify an unidentified object using standard analytical techniques.

At the same time, CLEA plans a systematic evaluation of its materials to find out how students and instructors regard the material and how effective it is in the classroom. Since the beginning of the project CLEA materials have been tested at Gettysburg College, and a wide range of informal responses have been received from users around the world. Though invaluable in fine-tuning the software and hardware, evidence of pedagogical effectiveness is anecdotal at best. Beginning in January 1996, however, an independent evaluator, Dr. Marcus Lieberman, began a formal evaluation process, including a program of pre- and post-testing of students in classes at Gettysburg and the University of Wisconsin, Madison. First results show that students using CLEA materials, and other hands-on exercises score significantly higher than students in lecture-only courses, an outcome we intend to explore more fully with a large sample of students and improved testing procedures. An extensive phone canvass of users is also being conducted.

Further work at CLEA is contingent, of course, on continued funding. But we note with pleasure that others are beginning to follow our lead. Translations of CLEA manuals into Spanish and Italian have already been made; French, Hebrew, and Chinese, we understand, are in the works. Instructors have been sending us copies of alternate student exercises and manuals they have developed, and alternate databases they have incorporated into our software. We note also the variable star exercises of Claud Lacy, of the University of Arkansas; Binary Maker, by David Bradstreet of Eastern College, Pennsylvania; the TS-24 telescope simulator by Craig Young, a New Zealand amateur; and a series of exercises on the web by Greg Bothun of the University of Oregon.

We look to the future with optimism. As astronomy education changed a century ago, so it is changing now. Astronomy classes in the future will offer a more experiential approach to the subject, and we take some satisfaction in knowing that Project CLEA has played a role in bringing this about.

5. Obtaining CLEA materials

CLEA materials are available over the world-wide web at URL

<http://www.gettysburg.edu/project/physics/clea/CLEAhome.html>

or can be downloaded from the anonymous ftp [io.cc.gettysburg.edu](ftp://io.cc.gettysburg.edu) (138.234.4.10). Manuals are available on-line as postscript files, but users who are unable to print these files can, or who cannot download the software, should contact us by mail: Project CLEA, Gettysburg College, Gettysburg, PA 17325 USA, by telephone, 717- 337-6028, or by email: clea@gettysburg.edu.

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