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Introducing astrophysics research to high school students

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Introducing astrophysics research to high school students

Eugenia Etkina†‖, Michael Lawrence‡ and Jeff Charney§
† *Graduate School of Education, Rutgers, The State University of New Jersey, 10 Seminary Place, New Brunswick, NJ 08901-1184, USA*
‡ *West Orange High School, 51 Conforti Ave., West Orange, NJ 07052, USA*
§ *Watchung Hills Regional High School, 108 Stirling Road, Warren, NJ 07059, USA*

This paper presents an analysis of an astrophysics institute designed for high school students. The study investigates how students respond cognitively in an active science learning environment in which they serve as apprentices to university astrophysics professors. The manner in which students implemented the behaviours of the experts with whom they were collaboratively engaged in a study of important cosmological questions was monitored and analysed. We found evidence that, by their participation in the program, students enhanced both (*a*) their content knowledge of unfamiliar physics and (*b*) their authentic practice of science in addressing contemporary cosmological problems. These results suggest that programs of this nature can support the development of expert science behaviours.

One way to implement scientific reasoning skills of logical argument, analysis of evidence and independent critical thinking is to place the students under the tutelage of a research scientist to gain the skills needed in scientific investigation [1]. The ways in which students model the experienced problem solver, the scientist, and the manner in which their thinking transforms as a result of an apprenticeship may provide insights into student learning.

As students are involved in actual scientific investigation, the expectation is that their thinking will change. If students are to model the expert, this thinking will have to change from descriptive or *what* type thinking [2] to a deeper thinking characteristic of explanation (*why* type questions). We want to describe our experience with high school students being placed into this situation during the Astrophysics Summer Institute at Rutgers University.

Program design

The program had two goals: (*a*) to investigate how much content knowledge increases relative to a national assessment through exploration in a non-traditional science learning environment and (*b*) to determine what specific behaviours of the expert scientists were adopted by the participants.

One practical way in which cosmology is studied is through x-ray analysis. X-ray spectra can reveal the physical condition of celestial objects, while the time variability can reveal their geometry, motion and interaction. X-rays are emitted by such celestial bodies as white dwarfs, neutron stars and black holes.

X-ray satellites collect information about these objects which is available for research via NASA Internet archives. These data, accessible through

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‖ E-mail: `etkina@rci.rutgers.edu`

the HEASARC website, can be downloaded, and analysed using a LINUX operating system. LINUX is a non-commercial operating system that can be installed free of charge on any IBM computer with enough memory.

It took us a year to prepare for the Summer Institute. We ran a pilot in one of the high schools to find out if data analysis and interpretation could be done by high school students (the results were positive). We then installed LINUX on 13 PC computers at Rutgers, developed and tested tutorials on the operating system and programs to be used for data analysis. We received $25 000 from Rutgers University for a four-week summer program to teach high school students to do research in x-ray astrophysics.

Twenty-four students ranked in the top 5% of their science classes from four central New Jersey High Schools and their physics teachers were selected for the program. The student group formed a population of urban and suburban high school sophomores and juniors from a wide ethnic and socioeconomic background.

Program structure

The Rutgers Astrophysics Summer Institute was split into two two-week segments. During the first two weeks, students and teachers were taught the basic physics, astrophysics and computer knowledge necessary to access and interpret x-ray archival data (see the appendix). This segment was done by a Rutgers professor of physics education. The subject matter was taught in an interactive mode, so that students and teachers could construct their own understanding of physical and astronomical phenomena [3]. The students were split into discussion groups with one teacher acting as a facilitator.

Students developed and then defended models of observed physical and astronomical phenomena. For example, after a discussion of Bohr’s postulates, students observed the emission lines in the hydrogen spectrum, measured their wavelengths, and using these results they derived the formula for energy transitions in hydrogen atoms:

$$E_n - E_m = -\left(\frac{2\pi^2 k^2 e^4 m}{h^2}\right)\left(\frac{1}{m^2} - \frac{1}{n^2}\right). \quad (1)$$

They then interpreted what transitions occurred to produce the observed spectral lines (transitions from third, fourth and fifth levels to the second level). The students developed their own procedures to investigate problems, used equipment to solve problems that arose in the discussions and proposed experiments to investigate phenomena. For example, after the discussion about the dependence of the stellar spectra on the surface temperature, students proposed looking for helium absorption lines in the solar spectrum.

The research part of the program was conducted by a Rutgers astrophysics professor. Students worked in groups of three using the Internet to retrieve NASA x-ray archival data from EXOSAT or ROSAT satellites that corresponded to certain x-ray sources. Using FTOOLS, students analysed light curves for periodicity. The analysis of the energy spectra allowed them to make predictions about the mechanisms of x-ray production (black-body, bremsstrahlung or synchrotron). The students collaboratively discussed the data patterns and tried to develop models that could explain the behaviour of the observed objects. The feasibility of the proposed models was debated with a leading astrophysics professor.

During the program, emphasis was placed on distinguishing structural elements of science—phenomena, models, quantities, laws, predictions, experimental testing and the reformulation of predictions and models. Major questions about celestial phenomena were posed which challenged students to develop an understanding of the difference between observational data and hypotheses. For example, the analysis of the observational data suggests that the quasars have radically different periodicities, as short as one day. What models account for such short periods and enormous luminosities? Students used different measurement units (such as joules and ergs) and mathematical tools (in one instance they derived the formula for the lifetime of the Sun by comparing different sources of energy) in order to consider such phenomena. Students graphed and analysed data. For example, after building a graph of luminosity versus temperature using data for the nearest stars, they essentially constructed the Hertzsprung–Russell diagram. Students also geometrically interpreted astronomical phenomena by developing different combinations of stars, luminosities and motions to account for observational data for spectroscopic binaries.

Methods

We used two formal and two informal means to assess the program.

Pretest, posttest and a questionnaire. At the beginning of the program students were given a pretest consisting of two questions. The first was a 1984 AP Physics ‘C’ exam problem (this was a level 2 question of moderate difficulty—see figure 1). A three-item posttest was administered on the last day of the four-week program. The first item of the posttest measured improvement in content knowledge in a general area of physics and was the same 1984 AP Physics problem. The second item was designed to indicate the effect of the program on acquisition of more rigorous content knowledge in physics involving angular momentum, mechanical energy and orbital speed. (See figure 2.) This item, a 1992 AP Physics free response problem 3, was more difficult ($X = 5.64$ out of 15 possible points) relative to the pretest free response 1984 #2 question ($X = 9.23$ out of 15 possible points).

The third item was a questionnaire to analyse the affective impact of the program.

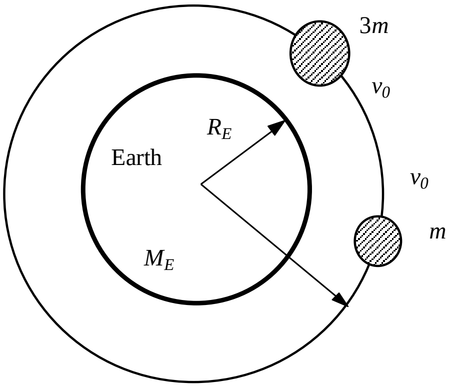
Journals. Students wrote a daily entry in a journal. Four questions were posed: (*a*) what was learned with respect to six categories (phenomena, models, physical quantities and their units, laws of physics, predictions, experimental testing of predictions), (*b*) what questions remained unclear, (*c*) what was liked and (*d*) what was disliked regarding the day’s events. The responses to these questions were addressed the next day.

Formative assessment. At the end of each day students were given ten minutes to discuss what they had learned. This process encouraged students to synthesize each day’s work, helped them to reflect and revealed conceptual difficulties.

Discussion group assessment. Students were frequently asked to answer questions, derive formulae, perform computations, devise models that explained experimental data and defend these models in front of the seminar.

Results

On the 1984 AP item, the posttest score (mean of 5.96) represents an improvement of 33.9% over the pretest score (mean of 4.45). While this score represents an improved performance on the posttest, it is not a large improvement.



Two satellites, of masses m and $3m$ respectively, are in the same circular orbit about the Earth’s centre, as shown in the diagram above. The Earth has mass M_E and radius R_E. In this orbit, which has a radius of $2R_E$, the satellites initially move with the same orbital speed v_0, but in opposite directions.

(*a*) Calculate the orbital speed v_0 of the satellites in terms of G, M_E and R_E.

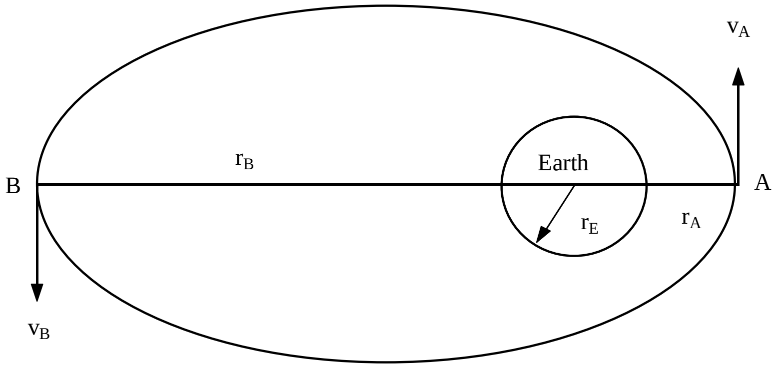
(*b*) Assume that the satellites collide head-on and stick together. In terms of v_0, find the speed v of the combination immediately after the collision.

(*c*) Calculate the total energy of the system immediately after the collision in terms of G, M_E and R_E. Assume that the gravitational potential energy of an object is defined to be zero at infinite distance from the Earth.

Figure 1. Pretest item from the 1984 AP Physics C Mechanics Exam.

On the 1992 AP item the participants scored an average of 6.88 out of a possible 15, while nationally the average score was 5.64. Our students’ average score was 22% higher than the score of the national pool of elite AP Physics students. Questionnaires indicated the following:

- 92% agreed or strongly agreed that their physics knowledge improved.
- 96% agreed or strongly agreed that they had a better understanding of the process of scientific inquiry.
- 83% would recommend the program to a fellow student.
- 71% preferred that their high school’s science courses followed the design of the program.



A spacecraft of mass 1000 kilograms is in an elliptical orbit above the Earth, as shown above. At point A the spacecraft is at a distance $r_A = 1.2 \times 10^7$ m from the centre of the Earth and its velocity, of magnitude $v_A = 7.1 \times 10^3$ m s^{-1}, is perpendicular to the line connecting the centre of the Earth to the spacecraft. The mass and radius of the Earth are $M_E = 6.0 \times 10^{24}$ kg and $r_E = 6.4 \times 10^6$ m, respectively.

Determine each of the following for the spacecraft when it is at point A:

(*a*) The total mechanical energy of the spacecraft, assuming that the gravitational potential energy is zero at an infinite distance from the Earth.

(*b*) The magnitude of the angular momentum of the spacecraft about the centre of the Earth.

Later, the spacecraft is at point B on the exact opposite side of the orbit at a distance $r_B = 3.6 \times 10^7$ m from the centre of the Earth.

(*c*) Determine the speed v_B of the spacecraft at point B.

Suppose that a different spacecraft is at point A, a distance $r_A = 1.2 \times 10^7$ m from the centre of the Earth. Determine each of the following:

(*d*) The speed of the spacecraft if it is in a circular orbit around the Earth.

(*e*) The minimum speed of a spacecraft at point A if it is to escape completely from the Earth.

Figure 2. Posttest item from the 1992 AP Physics C Mechanics Exam.

Discussion of results

The statistical analysis indicates that the participants performed significantly better on the 1992 problem of the highest difficulty level. The AP Physics C Mechanics Exam was given to approximately 10 000 students in 1992. That was approximately 1.5% of all the students in the US (660 000) who took physics in high school. So, it can be safely stated that the AP population represents the very best physics students in the US. Still, after a year of coursework and exam review, these ‘elite’ students received an average of 5.64 out of 15 on this item, an item that was developed by the College Board. The low score can be explained by its level of difficulty. The Rutgers participants did not study for this item, unlike high school Advanced Placement physics students who spend long periods of time preparing for the exam by doing numerous AP problems. Our students, with no formal AP course and no review, did significantly better than the elite group who had. We believe the participants’ performance resulted from the emphasis and the application of concepts. These concepts were used to explain astrophysical phenomena.

A number of studies justify our non-traditional approach. In a study of problem-solving instructional methods in the high school setting, Huffman [4] found that different problem-solving strategies do not significantly improve students’ conceptual understanding:

> Hewitt [5] claimed that in high school, problem-solving interaction actually obscures students’ understanding of the con-

> cepts; he recommended teaching the concepts and principles of physics instead of problem solving. If Hewitt is correct, the time and effort that teachers devote to problem solving may be better spent on the concepts and principles of physics. [4]

There was no significant improvement on the pretest problem based on the 1984 problem of moderate difficulty. The participants had an average score of 2.85 out of a possible 11 on the pretest, and improved (but not significantly) to a score of 3.7 on the same item during the posttest. This occurrence may be explained by the fact that there were only two parts to the 1984 item, as opposed to five parts for the 1992 item. Our analysis suggests that the participants were not afforded as much opportunity to demonstrate an improvement in their knowledge because of fewer questions.

The discussion group assessment revealed expert behaviours that included development of models, the defending of models, the testing of models through prediction and the revision of models. These student behaviours were strongly associated with those exhibited by the scientists who instructed the program. The cycle of building models, providing explanations, defending models before peers, sometimes rejecting these models due to feedback and ultimately reformulating new models may well have become integrated in the novices' schemata through meaningful socialization [6]. Data from the student journals suggest that these experiences were recognized as being very different from the type of learning experienced by students in their traditional high school science classrooms.

Finally, it is clear from the written responses that students enjoyed the program. In addition, they reported that they improved their knowledge and understanding of science. The following comments were typical: 'I enjoyed the process of discovery, being given just the bare essentials to construct a model of the workings of cosmic objects and the universe itself.' 'I enjoyed being in a program where you learn for the sake of learning rather than like in a school where you learn to do well on tests.' 'I liked the challenge of trying to figure things out on our own.' The cumulative affective result of the program has reinforced for us the notion that our pilot program was successful. With appropriate changes in our pretest and posttest items, and more careful monitoring of what expert behaviours developed, we feel the program will grow.

Implications

Science is an enterprise [7] in which hypotheses are generated and data gathered to support or disprove hypotheses. Frequently, when hypotheses are found to be incorrect, they are revised—a critical scientific process. The program gave students the opportunity to practice science by engaging in an 'activity that allows learners to discover, interact and build their own understandings and meanings' [8]. Data were presented or obtained by students in seminar, lab and Internet exploration. Students were asked to advance and defend hypotheses to account for often-unfamiliar data. Although they knew little beyond a minor foundation of physics (one year of high school physics), they were able to build models 'assimilatively' [9] based on inferences of data that summarized abbreviated bodies of facts in astrophysics. This process can work powerfully to introduce many technical and sophisticated concepts to novice learners [10]. In short, students were modelling expert behaviours.

The program also embodied the philosophical nature of science. Exploration and inquiry were an underlying component of our discussions. When gravity, for example, would not account alone for the unique behaviour of a rapid burster, a newly discovered type of pulsating star, other explanations were called for by students (magnetic fields, as one example). The students learned first-hand that the process of providing an explanation is dynamic and involves building a model, and then evaluating and improving the model iteratively until the new phenomena were satisfactorily explained. Furthermore, this process is one that is advocated by several science education reforms [7, 11].

Finally, the realization by students that science is a changing body of knowledge was an unexpected outcome of the program. The speculative nature of the phenomena we studied generated many questions. A common response by the expert was an informed but disquieting, 'We just don't know the answer to that question'. Questions such as 'How do rapid bursters form?' and 'What are the sources of quasars' energy?'

constitute difficult but exciting science. At first students felt uncomfortable with the lack of closure to ‘We just don’t know’. Yet this answer was often framed within a large expanse of related knowledge that has grown substantially since the launch of the Hubble telescope. In this program students acquired an authentic scientific sense that study of this new material generated more questions than answers—a very different experience from the textbook-based known bodies of knowledge that had been the foundation of their educational experience.

During this school year all students began research in their schools, using LINUX installed on their school computers. They meet with Rutgers faculty once every two months to discuss their work and between the meetings communicate via e-mail and Internet bulletin board. We cannot report any major discoveries or new findings yet but the work is in progress.

Acknowledgment

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Appendix

Physics and astronomy material covered in the program:

1. Wave nature of light. Quantum nature of light.
2. Radiation of electromagnetic waves, laws of radiation. Absorption and emission spectra. Incandescent light bulb spectrum.
3. Solar spectrum.
4. How is a stellar spectrum formed? What do we expect to see in spectra of different stars? What can we learn from a stellar spectrum?
5. How do we measure distances to celestial objects?
6. Luminosity and brightness. How do we calculate the luminosity of the Sun?
7. Absolute and apparent stellar magnitudes.
8. What are stellar parameters? How do we determine stellar parameters?
9. Spectral sequence. H–R diagram and its meaning.
10. How long will our Sun shine?
11. Stellar evolution to and off the main sequence. Binary stars.
12. White dwarfs and neutron stars. Pulsars and how we interpret their radiation.
13. Novae and supernovae stars.
14. Black holes.

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