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Using the Big Ideas in Cosmology to Teach College Students

Kim Coble,[1] Lynn R. Cominsky,[2] Kevin M. McLin,[2] Anne J. Metevier,[2] and Janelle M. Bailey[3]

[1]*Chicago State University, Department of Chemistry and Physics, 9501 South King Dr., Chicago, Illinois 60628, USA*

[2]*Sonoma State University, 1801 East Cotati Ave., Rohnert Park, California 94928, USA*

[3]*University of Nevada, Las Vegas, Department of Teaching and Learning, 4505 South Maryland Pkwy Box 453005, Las Vegas, Nevada 89154, USA*

Abstract. Recently, powerful new observations and advances in computation and visualization have led to a revolution in our understanding of the structure, composition, and evolution of the universe. These gains have been vast, but their impact on education has been limited. We are bringing these tools and advances to the teaching of cosmology through research on undergraduate learning in cosmology as well as the development of a series of web-based cosmology learning modules for general education undergraduate students. Informed by our research on student learning in cosmology, we are utilizing best pedagogical practices to implement the content in an accessible online student-centered framework. In this workshop, we engaged participants with examples of interactive exercises, illustrations and text from the initial module of the three-module curriculum. We invite interested educators to help us test the materials with their students as the curriculum develops.

1. Introduction

Recent results of cosmology research have revolutionized our understanding of the universe. While we have known for some time that the universe was much hotter and denser in the past, and that it has been expanding and cooling for billions of years, new detailed observations and computer simulations show us directly what our universe was like at various epochs in the past, how it appears today, and how it will evolve in the future. Through observations and measurements of distant supernovae, field galaxies, galaxy clusters, the cosmic microwave background, abundances of light elements, gravitational lensing, and more, we can answer fundamental questions about the composition of the universe, its geometry, its age, how structures are distributed and formed, and even the fate of the universe.

Needless to say, undergraduate astronomy courses have had difficulty staying current with rapidly unfolding cosmological knowledge. Modern topics, such as cosmology, are of primary interest to many educators and students (e.g., Pasachoff 2002), but we are only beginning to understand students' alternative conceptions in this area (Prather et al. 2002). Furthermore, according to a survey by Bruning (2006), only ~20% of a typical introductory astronomy textbook is devoted to cosmological topics. With calls for science education reform at all levels (American Association for the Advancement of Science 1990, 1993; Bransford et al. 1999; Fox & Hackerman 2003; National Research Council 1996, 2003), it is imperative that we design effective instruction to counteract student misconceptions, build upon correct ideas, and provide scaffolds for new understanding (Donovan & Bransford 2005).

We have structured our research and curriculum development around three cosmological themes: (1) structure: the universe is vast in space and time, (2) composition: the universe is composed of not just regular matter, but also dark matter and dark energy, and (3) change: the universe is dynamic and evolving. We also emphasize how this knowledge is supported by observational and experimental evidence and that the processes occur according to the laws of physics.

Our goals for the workshop were to give participants an overview of the curriculum and an opportunity to use some of the interactive exercises. After each topic in the workshop, we presented the relevant results of some of our cosmology education research, which has informed the curriculum. The curriculum and the research are each described further in the sections below.

2. Curriculum

Informed by our research on student understanding of cosmology, we are creating an immersive set of web-based modules that allow students to participate in the process of doing science while learning cosmological concepts. Text, figures, and visualizations are integrated with short and long interactive tasks, which use real cosmological data.

2.1. Organization of the Modules

Table 1 shows the preliminary organization of the curriculum into three modules. Each curriculum module consists of a central theme, with five chapters that can each be pursued over the course of one week. The chapters are further subdivided into sections that focus on a specific topic.

2.2. Pedagogical Approach

Our goal is to move beyond typical curricula, which are predominantly text-based with occasional animations or simulations, toward an environment that realizes a higher level of learner-centered interactions. Our ultimate goal is to create a simulated world in which learners choose their own path to knowledge, much like professional researchers. Such learning experiences provide the most engaging connection to the material, and they go far beyond what has traditionally been possible with textbooks and other passive media such as film.

The pedagogical flow of a section topic is shown in Figure 1. First, student ideas are elicited with a short warm-up question. Insights from cognitive psychology have shown that perceptions are related to prior experiences and current knowledge. Students enter into a course with different mental representations, and these representations can affect their learning. We need to know where the students are in order to take them where we want them to be. We also must explicitly make connections to existing ideas. The warm-up questions target commonly held student ideas as a precursor to learning the chapter material. Next, having thought about the topic themselves, students complete section readings and one or more short, interactive tasks. These tasks have

Table 1. Preliminary Curriculum Content

Module	Chapter
Our Place in the Universe: Space and Time	1. The Size and Scope of Space 2. Observing the Universe: Light and Telescopes 3. Motion and Time 4. Measuring Distances 5. Special Relativity and Spacetime
The Darker Side of the Universe: Gravity, Black Holes, and Dark Matter	6. Classical Physics: Gravity and Energy 7. General Relativity 8. Black Holes and Spacetime 9. Observing Dark Matter Through the Motions of Objects 10. Observing Dark Matter Through Gravitational Lensing
Our Evolving Universe: Past, Present and Future	11. Expansion and the Hubble Law 12. The Early Universe 13. The CMB and Large Scale Structure Formation 14. Dark Energy and Supernovae 15. Geometry and the Fate of the Universe

styles familiar from education research: ranking, sorting, matching, visual, etc. Finally, students are asked questions to summarize what they have learned by keeping guided notes. By integrating the activities in this manner, students can master a narrow topic before moving on to the next. A student "logbook" provides a framework to tie the work together and allows the instructor to track a student's progress and grade it for effort.

Each chapter features a longer "lab" activity that includes real cosmological data and integrates the concepts learned in the chapter. A "mission report" on the activity can be graded by the instructor. There is also a customizable homework section with problems automatically graded for accuracy. Other features include a scientific calculator, graphing tools, a glossary, and instructor resources.

Any math involved in the activities (high school algebra at the most) is explained conceptually as well as numerically, in order to empower students rather than frustrate them. All examples for the numerical exercises follow a consistent step-by-step approach for problem solving: "Given, Find, Concept(s), Solution, Think About Answer."

Not only have computer simulations and visualizations revolutionized our understanding of cosmology, but students themselves underscore the need for good visuals during interviews. One student explains how a good visualization would help her replace incorrect old ideas:

> QueenB: "I've always heard about the Big Bang Theory and how it was this big explosion and that's how the planets and everything else came about. . . I don't really remember what the actual Big Bang Theory is now,

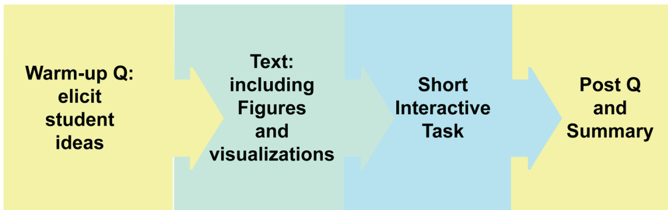

Figure 1. Pedagogical flow of a section (narrow topic focus) within the curriculum.

> but I do know that I was told otherwise in my new class... [but] I need some kind of visual to explain to me how things work in science."

We do not simply show visualizations, but have created exercises to help students understand what they are seeing, because students do not necessarily view them from the same perspective as astronomers. Furthermore, as much as possible we compare models and data and make it clear which is which.

We feel that it is important to include real cosmological data in the curriculum not just because it is a cornerstone of science, but because our research shows that this is important for students. Pre-course surveys show that students are initially skeptical that, for example, the age of the universe is measurable or that the Big Bang model is supported by evidence. In end-of semester interviews, two students describe the value of real data and interactive engagement in understanding the material and in changing their beliefs:

> BigDipper: "Actually, when you told me, I was less inclined to believe it, to tell you the truth... I really didn't understand... At first I thought a lot of scientists kind of sometimes make up facts... I never understood it, so I thought a lot of stuff was made up... Now I do, now that I saw the calculations. And done [sic] it myself."

> Kenya: "We did it during the lab, which was awesome... we took pictures of galaxies and we actually measured them and we recorded them on the graph and we actually came up with real authentic data from real galaxies... it was really real authentic information, so I got a lot from that..."

2.3. Sample Interactives

The warm-up questions and short interactive tasks are chosen and designed based on our research on student strengths and needs. During the workshop, we presented examples from the first four chapters of the curriculum. Again it should be noted that these activities are all embedded within a full-curriculum and are not intended as stand-alone interactives.

Chapter 1: Starter Question. Warm-up questions such as the example below are typically found at the beginning of a section, are meant to elicit student ideas, and are presented in "student voices." In the workshop, we presented them to participants as clicker questions. In the curriculum, students will choose from a menu of options, and explain their choices in their logbook. The starter question from Chapter 1 involves the hierarchical structure of the universe:

> Three students are discussing which objects are in our solar system.
>
> Annie says, "A solar system has different things in it like galaxies and planets and stars and stuff like that. Our solar system has the planets Mercury, Venus, Earth, and so on. The planets have moons so I think moons too."
>
> Brenda says, "I disagree. I think a galaxy has stars inside it. Each one of the stars has planets orbiting around it and that's what a solar system is. So a galaxy has solar systems in it but a solar system doesn't have galaxies in it."
>
> Charles says, "I think that the terms solar system and galaxy mean the same thing."
>
> Do you agree with any of these students, and if so, who? Explain your reasoning in your logbook.

Chapter 1: Structure Hierarchy. The first interactive that participants tested was also from Chapter 1, dealing with the hierarchical structure of the universe (Fig. 2a). In this activity, students must place common objects in the universe in a hierarchy to show how they relate to one another.

Chapter 2: Photon Races. The next warm-up question (Fig. 2b) was again done as a clicker question with workshop participants. It targets student ideas about the speed of light for different colors:

> Ladies and gentlemen! Place your bets! Which color of light do you think travels fastest through the vacuum of empty space? In your logbook, rank the following from fastest to slowest:
>
> • Radio • Optical • X-ray • Gamma-ray
>
> In your logbook, describe how the outcome of the race compares with your initial predictions. Explain how the equation that describes the relationship between a wave's wavelength and frequency ($\lambda = c/f$) relates to the outcome of the race.

Chapter 3: Lookback Time. In this interactive activity, students are presented with a star field with an "observer" star in the center (Fig. 2c). At the top of the star field, students are given the order in which three stars go supernova and the time between each event. Students must determine the order in which the light signals from the supernovae will be seen by the observer star. The primary goal for this activity is to confront students with the relationship between distance and lookback time; that it is not just the timing of an event that dictates when it is observed but also its distance from the observer. Several easier activities relating to lookback time precede this one in the curriculum.

Chapter 3: Measuring Redshift. This is an example of an activity that uses real data. Here students use spectra of galaxies (in an intensity vs. wavelength format) and the redshift formula in order to determine the velocities of several galaxies (Fig. 2d). A scientific calculator and answer-checker will eventually be built into the full web-based system. However, for the purposes of the workshop, we programmed the activity to perform some calculations for participants.

Chapter 4: Parallax. In this activity, students must use a conceptual understanding of parallax to rank stars by distance. They are shown a star field and can adjust the position of the Earth around the Sun to observe the stars shifting back and forth.

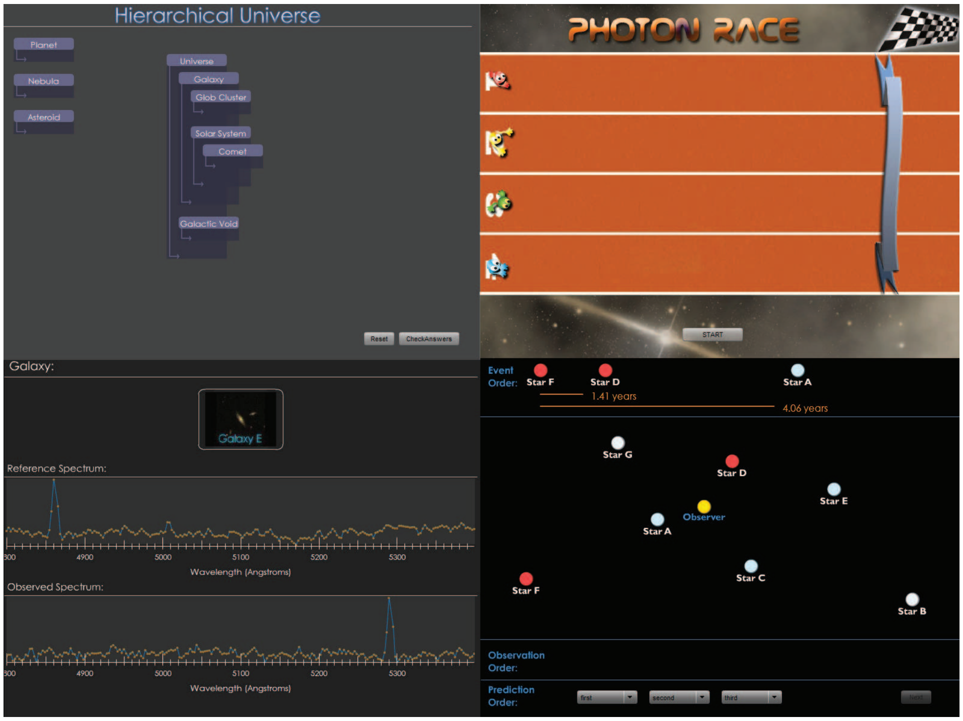

Figure 2. Sample Interactives. From top left to bottom right: (a) Hierarchical Universe, (b) Photon Races, (c) Quantitative Redshift, and (d) Lookback Time.

3. Research

Determining the range and frequency of “alternative conceptions” is an important first step to improving instructional effectiveness. Through analysis of pre-instructional open-ended surveys at four different institutions (N = 703), follow-up interviews (N = 14), and pre-course essays, laboratory assessments, and exams over five semesters at a single university ($N \approx 60$), our research group is attempting to classify students’ ideas about concepts important to modern cosmology. The areas targeted so far include the universe’s structure, age, evolution, and composition (including dark matter and dark energy), as well as student perceptions of astronomical distances. Survey responses, analyzed through an iterative process of thematic coding, reveal a number of alternative conceptions. Findings from pre-instructional interviews and homework essays are consistent with results from the multi-institutional surveys. Post-instructional interviews reveal student progress toward more expert-like ideas as well as areas for improvement, plus student attitudes toward inquiry-based instruction. In the workshop, we presented the research results for topics most relevant to Module 1, namely structure and distances.

3.1. Structure

Survey results indicate that students frequently conflate structure terms such as solar system, galaxy, and universe, or do not understand the relationship between the terms (Table 2). Early interviews confirm results from the written surveys that students do not have a concrete understanding of the structure of the universe. Students do have some knowledge of the objects in the universe, but their understanding of the structure of the universe is superficial.

Table 2. Survey results on structure. *"Describe each of the following: galaxy, constellation, solar system, universe. Are any of these related? If so, how?"* Responses are described as "OK" because extremely few were what we would call correct. For example, an OK response might be that a solar system contains stars and planets. The same OK response would also be acceptable for a galaxy.

	OK (%)	Incorrect (%)	No Response
Galaxy	77	12	11
Solar System	87	9	4
Universe	92	1	7
Hierarchical Relationship	60	27	13

Later interviews and exams reveal that students' understanding of structure does increase by the end of the semester. One student described her learning process as follows in an interview:

> Pierce: "Like I kind of thought the galaxy was the universe, and the universe was something they just talked about like when kind of, you know constellation oh that's the universe. That's what I thought the universe was. I didn't know, I just thought it was referring to stars or something."

3.2. Light and Spectra

Student misconceptions about light and spectra are well-documented in the literature (e.g., Bardar 2006; Comins 2001; Zeilik, Schau, & Mattern 1998). One common source of confusion is the difference between frequency and speed. For example, when questioned deeply, a teacher who participated in NASA's *Multiwavelength Universe* summer program in 2011 (which used activities from Chapter 2 of our curriculum) explains her ideas:

> "Another thing scientists like to know about EM [electromagnetic] waves is how fast they travel. To do this, they calculate how many waves move past in one second. This is called the frequency. . . A wave that travels very fast has a high frequency. A wave that travels slower has a low frequency. EM waves that have a short wavelength move faster than waves that have a long wavelength, so short waves have a higher frequency than long waves . . . The amount of energy contained in an EM wave depends on how fast it moves. That means that shorter wavelength waves, which have a higher frequency, have more energy than longer wavelength waves, which have a lower frequency."

This same teacher had responded to an earlier, lower-level question saying that all light waves travel at the same speed. This kind of varied response demonstrates the need for instructors to probe deeply into their students' ideas.

3.3. Light Travel Time

One of the key concepts that students must learn in order to understand other aspects of cosmology is the relationship among distance, speed, and time, particularly light travel time. Unfortunately this concept is surprisingly difficult for students. Two examples of the pre- and post-test questions that we used to probe student understanding are shown below. The pre-test questions are given after lecture but before lab activities (different than those designed for this curriculum) and the post-test questions are asked on exams. Results are presented in Table 3. Follow-up interviews suggest that students who have difficulty with astronomical sizes and distances have been more strongly influenced by culture and the media, whereas those who had less difficulty expanded on their personal prior experiences.

> Pre-test (N = 57): In the future, when space travel is advanced, you have 3 weeks of vacation time and want to visit the star Sirius, in honor of your favorite Harry Potter character. Sirius is 8.6 light years away. If spaceships in the future could travel at half the speed of light (much faster than current spaceships), would you be able to make the trip to Sirius and back during your vacation? Explain.
>
> Post-test Q (N = 62): The star Vega is 25 light years away. If you were in a spaceship that could travel at half the speed of light, the amount of time it would take you reach Vega is ___________ . (Be specific, use a number.)

Table 3. Research results for half-speed of light travel time questions. An incomplete response is missing one or more of the identified elements of a correct answer, whereas a "partial" response contains both incorrect and correct elements. On the post-test, the most common wrong response was to divide by 2 instead of multiply by 2.

	Pre (%)	Post (%)
Correct	14	40
Wrong	32	44
Incomplete	23	10
Partial	23	6
True but Irrelevant	7	0
Non-Scientific	0	0
No Response	2	0

3.4. Parallax

In order to assess their understanding of parallax, students were given the question in Figure 3 post-lecture but prior to interactive class activities (different than the ones developed for this curriculum). The question also appeared on exams after activities and homework on the material.

Post-lecture, but prior to the activities on parallax, 28% of students (N = 36) answered correctly. On a midterm exam following the activity, 56% of students (N = 43) answered correctly. On the final exam, 58% of students ($N = 45$) answered correctly. The most common incorrect response was that the star that shifts more is farther away.

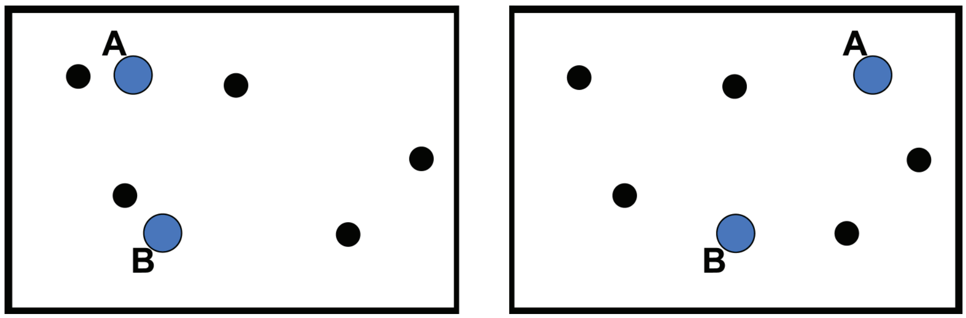

Figure 3. The following two pictures were taken six months apart. Which star is farther away, A or B? How do you know?

4. Evaluation and Open Invitation

Throughout the workshop and at the end, participants were invited to fill out a survey, providing feedback on the workshop materials. We are grateful to the 16 participants who did so; we will be incorporating this feedback into our curriculum development. Participants offered particularly useful specific critiques and suggestions in the free response section.

When asked about the instructions for the interactives, responding participants generally were able to understand the instructions well enough to do the activities and, similarly, found the instructions easy to follow. Only two or fewer participants disagreed with either statement among three of the activities. However, about a third (6) of the respondents had trouble with instructions for the *Hierarchical Universe* activity. While participants could follow and execute the current instructions, many of them nevertheless also suggested that some changes be made to the instructions.

Participants overwhelming felt that their students would respond positively to the interactives, with only one or two respondents disagreeing with any of the four relevant items in this question set, for any of the four activities. More specifically, participants felt that the activities would attract their students' use (by being interesting and engaging), and that students would learn from the activities, particularly by addressing misconceptions. For the most part, respondents strongly agreed with the value of the activities for addressing misconceptions, and all 16 respondents "strongly agreed" that *Hierarchical Universe* would address some misconceptions. The ratings for *Quantitative Redshift* were slightly less positive than for the other activities.

This workshop was the first time that any of our curriculum materials have been tested outside of our development group. We are eagerly seeking instructors to pilot-test Module 1 in their classes starting in January 2012. We feel that it is important to develop and pilot-test the curriculum with a diverse range of institutions and students from the onset of the process. Physics and astronomy education research has had a major impact on how we view student learning and many materials developed as a result have been shown to be effective. However, materials have often been developed at large R1 research universities with traditional college students. The institutions that have already signed letters of commitment for pilot-testing include community colleges, undergraduate institutions, research universities, and one online university; some of these are minority-serving institutions. We are also seeking cosmologists with data or simulations that can be incorporated into the curriculum. If you would like to sign up for pilot-testing or to contribute cosmological data, please contact the authors.

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