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Investigating Student Ideas About Cosmology III: Big Bang Theory, Expansion, Age, and History of the Universe

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Abstract

We have undertaken a multi-semester study of student ideas in an undergraduate general education astronomy integrated lecture and lab course with a focus on active learning at an urban, minority serving institution. We collected individual interviews ($N = 15$) and course artifacts ($N \sim 60$), such as pre-course homework essays and midterm and final exam questions in a variety of formats. Continuing our work from a previous study (Coble *et al*. 2013), here we examine student ideas with regard to the Big Bang Theory, expansion, age, and history of the Universe. We find that a significant fraction of students hold alternate conceptions, including: the Big Bang Theory describes the creation of planets and/or our Solar System; the "Big Bang" refers to an explosion within a small point or mass; there is no evidence in support of the Big Bang Theory; the Universe has always existed; and stars, galaxies, and/or planets formed at the same time or very soon after the creation of the Universe.

1. INTRODUCTION AND PURPOSE

Recent results from 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 reveal directly what our Universe was like at various epochs in the past, how it appears today, and how it will evolve in the future.

Student knowledge of cosmology is important; understanding the underpinnings of the Universe can deepen students' sense of wonder and help them appreciate where they come from, in the broadest sense. Since cosmology is an active area of astronomical research that can garner attention in the media, it may be of greater appeal to students than some other topics in astronomy. A number of groups in the education community have stressed the need to incorporate modern cosmology topics and research results into astronomy education. For example, the *National Science Education Standards* (National Research Council [NRC] 1996), Project 2061's

Benchmarks for Science Literacy (American Association for the Advancement of Science [AAAS] 1993), and *A Framework for K-12 Science Education* (NRC 2012) guiding the development of the Next Generation Science Standards (Note-1) require student learning of cosmology at the K-12 level. Pasachoff (2002) and Donovan and Bransford (2005) have called for increased coverage of modern research results, designing effective instruction to counteract student misconceptions, and providing a more complete treatment of science (e.g., a treatment in which students work with real astronomical data to come to new understandings).

1.1. Conceptual Framework

A first and important step in supporting student learning of modern cosmology is to determine the range and frequency of alternate conceptions. Alternate conceptions refer to the beliefs, ideas, and theories that people construct in an attempt to make sense of their world (e.g., Ausubel 1968; Driver and Easley 1978; Posner *et al*. 1982; Zirbel 2004). These alternate conceptions differ from the consensus ideas of scientists. Constructivist learning philosophy emphasizes that students acquire new knowledge by assimilating it into their existing framework of understanding (Carpenter and Lehrer 1999; Riggs and Kimbrough 2002; Slater, Carpenter, and Safko 1996). In order for this new knowledge to have a solid foundation, it is essential that we directly address the alternate conceptions students bring to the classroom (Bransford, Brown, and Cocking 1999). As Bell, Brook, and Driver (1985) wrote, “This may involve refining the ideas students already have and helping them extend their range of applicability or in some cases, through challenging them, to encourage students to modify or change their conceptions” (p. 211). The purpose of this study is to investigate students’ ideas in cosmology by sub-topic, providing astronomy educators with a starting ground for facilitating conceptual change.

1.2. Previous Research

Numerous studies have examined student alternate conceptions in geocentric aspects of astronomy (e.g., seasonal change: Atwood and Atwood 1996; Kikas 2004; Ojala 1997; Zeilik and Morris 2003; the shape of the Earth: Vosniadou 1994, Vosniadou and Brewer 1992; Vosniadou *et al*. 2001; the day/night cycle: Atwood and Atwood 1997; Kikas 1998; Vosniadou and Brewer 1994; and moon phases: Lindell 2001, Trundle *et al*. 2002, 2003; see also Bailey and Slater 2003 and Lelliott and Rollnick 2010, and references therein). Other studies have presented students’ alternate conceptions of stars (Agan 2004; Bailey *et al*. 2009) and size and scale (e.g., Cheek 2012; Delgado *et al*. 2007; Tretter, Jones, and Minogue 2006; Miller and Brewer 2010).

Studies of student ideas with regards to cosmology have lagged behind somewhat. Fortunately, important progress has been made (e.g. Prather, Slater, and Offerdahl 2002 and recently Wallace, Prather, and Duncan 2012a). Prather, Slater, and Offerdahl (2002) surveyed nearly 1000 middle school, secondary school, and undergraduate students prior to instruction. They found that 94% of undergraduate students had heard of the Big Bang Theory. Of the undergraduates who had heard of this theory, approximately half indicated that the theory describes the creation of the Universe, while another third said it relates to the creation of planetary systems. Responses from the remaining 21% of undergraduate students were categorized by the authors as “other.” Simonelli and Pilachowski (2003) similarly found that approximately 15% of the 148 ASTRO 101 students they surveyed said the Solar System is formed out of the “Big Bang” (Note-2), an idea that has also been observed in geoscience education research (e.g., Libarkin, Kurdziel, and Anderson 2007; Marques and Thompson 1997; Trend 2001a).

Prather, Slater, and Offerdahl (2002) noted that within the creation of the Universe category, 80% of undergraduate students think of the Big Bang Theory as describing an “explosion of pre-existing matter” prior to instruction. Wallace, Prather, and Duncan (2012a) similarly found that 52–56% of undergraduate students refer to the Big Bang Theory as describing an explosion and an additional 28–38% discuss pre-existing matter. Wallace, Prather, and Duncan (2012a) also presented a related alternate conception that there is a center to the Universe, a view expressed by 7–30% of students (see also Trumper 2000 and Kalkan and Kiroglu 2007 for similar results). In terms of the subsequent expansion of the Universe, a number of studies have shown that prior to instruction, students are often unaware of the fact that the Universe is expanding (Lightman *et al*. 1987; Lightman and Miller 1989; Prather, Slater, and Offerdahl 2002; Wallace, Prather, and Duncan 2012a).

Another important aspect of cosmology education research relates to students’ understanding of large timescales—including the age of the Universe and when major cosmological events occurred. Most of the research in this area comes from geoscience education and, accordingly, focuses on Earth’s history (as explained in Grundstrom, Slater, and Stassun 2008). Notably, Trend (1998, 2000, 2001a, 2001b) conducted a series of studies examining student understanding of geological time; e.g., “the period from just before the formation of Planet Earth to the first appearance of humans” (Trend 2001a, p. 309). In his 1998 pilot study, middle school students volunteered the phrase “Big Bang,” often equating it with the asteroid that killed the dinosaurs. Trend then provided the “Big Bang” as an event option in subsequent studies. Across his studies, he found that people significantly overestimate how long it has been since the “Big Bang” occurred. For example, in Trend (2000) he surveyed 179 pre-service primary school teachers and found the majority listed the “Big Bang” as having happened more than 1×10^{12} (i.e., more than one trillion) years ago.

1.3. Research Questions

This article is one of a series examining the nature and frequency of undergraduate student ideas around three major cosmological themes: (1) structure—the vast distances, timescales and hierarchical nature of structure; (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, exemplified by the Big Bang Theory and expansion of the Universe. Our aim is to thoroughly catalog student ideas, from a single institution, using multiple data sources. We are interested in documenting not only students’ pre-instructional ideas as other studies have done, but the range of student ideas as sampled over the course of the semester (e.g., Sayre and Heckler 2009). We use a mixed-methods approach including both qualitative and quantitative data to form a deeper understanding of student ideas. A mixed-methods approach using multiple data streams can be a powerful approach to research questions, allowing for comparisons and providing a rich, flexible data set (Beichner 2009; Kregenow, Rogers, and Constas 2010).

In this article (Paper III), we use course artifacts and in-depth interviews collected at Chicago State University (CSU), a minority serving institution on Chicago’s Southside, to examine student ideas on the Big Bang Theory, expansion, age, and history of the Universe. Using a similar methodology, in Coble *et al.* (2013, Paper I) we analyze and discuss student ideas on the distances and structure of the Universe. In Coble *et al.* (in preparation, Paper II), we examine student ideas on the composition of the Universe. We have also collected information about the geometry, accelerating expansion, and fate of our Universe, which will form the basis of a future analysis. This approach complements that of Bailey *et al.* (2012), where we presented the results of a nationwide, open-response, pre-course survey on various cosmological topics, including distances, structure, composition, Big Bang Theory, and age of the Universe.

In Section 2 of this paper, we describe our methodology, including the setting, participants, data sources, and analysis procedure. We then present the results and implications from our analysis of student ideas on the Big Bang Theory (Section 3), the expanding Universe (Section 4), the age of the Universe (Section 5), and the history of the Universe (Section 6). These data are presented chronologically as they were sampled throughout the semester, alternating results and implications for each sub-topic. In Section 7, we conclude with a discussion of our most important results.

2. METHODS

2.1. Setting and Participants

We collected and analyzed data taken from CSU’s introductory astronomy course over five semesters: Fall 2008, Spring 2009, Spring 2010, Fall 2010, and Spring 2011. The demographics of the students in the classes are representative of the university’s undergraduates as a whole (84% African-American, 7% Latino, 71% women, median age ∼25; The Office of Institutional Effectiveness and Research, 2011).

The course is an integrated lecture and lab course that meets four hours per week for 15 weeks, with approximately 15 students per semester. Coble taught the course all semesters except Spring 2011 during which Trouille taught the course using Coble’s curricular materials. The astronomy course covers the major topics typically taught in an ASTRO 101 course (Slater *et al.* 2001), with more of an emphasis on cosmological topics than is typical.

As a guiding principle for the class, we support students in learning both the content and processes of science, including making predictions and testing them experimentally, relating science to everyday life, and reflecting on results. The class forms a scientific community. Ours is an active classroom in which interactive lectures are integrated with short and long tasks, such as CSU worksheets, *Lecture-Tutorials* (Adams, Prather, and Slater

Table 2.1. Relative schedule of topics, cosmology-related lab activities, and data collection points. The schedule was the same for all five semesters of data collection. Interviews with students (labeled A-O) were collected over four semesters

Weekly topics	Laboratory[a]	Assessment/interview[b]
Introduction; Scale of the Universe		
Scale of the Universe; Process of Science; History of Astronomy	Lab#1: Scales of the Universe	HW #1 due
Looking at the Sky; Seasons		Lab #1 due
Moon Phases; Motion, Gravity, Energy		
Motion, Gravity, Energy; Light		
Light and Telescopes		Exam #1 ($N_{max} = 65$)[c]
Solar System: Exploration, formation, climate change, Exoplanets		
The Sun; Stars: Lifetimes, properties, classification		Interview: A
Stellar evolution; Our galaxy		Interview: B
Other galaxies; Dark matter	Lab #8: Mass of galaxies	Interview: C
Measuring distances	Lab #9: Measuring distances	Lab #8 due Interviews: D, E
Expansion and age of the universe	Lab #10: Hubble law	Lab # 9 due Interview: F
Big Bang theory, history of Universe, Fate of Universe		Lab #10 due Interview: G
Observing project review panel	"Galaxy challenge"	Interviews: H, I
Life in the universe		Exam #3 ($N_{max} = 56$) Interviews: J, K, L
Present observing projects, review		Interviews: M, N
Final exam		Final exam ($N_{max} = 58$) Interview: O

[a] Labs #2-7 and Exam #3 do not relate to cosmology topics and so are not included here.

[b] Assessments due or completed at the beginning of class. Interviews conducted prior to instruction on that week's topic.

[c] N_{max} is the maximum number of responses to questions on a given exam. The number of responses might have been less for specific questions because not every question was asked every semester. The number of responses for each question is presented in the relevant data tables.

2005) (Note-3), activities from *Mastering Astronomy* (Note-4), and longer laboratory-oriented activities. Students also complete an observing project using the Global Telescope Network (Note-5). A CSU-developed course workbook ties materials together. We will provide more details on the activities relevant to specific cosmological topics as student ideas are addressed later in this article.

The course schedule, as well as a list of when various data were collected, is given in Table 2.1. Weekly topics include material covered in lecture, laboratory, and other activities. The schedule was the same for all five semesters of data collection. Interviews were conducted over four semesters and occurred prior to that week's instruction.

2.2. Data Collection Instruments

The data consist of pre-course homework essays ($N = 55$), exam responses ($N \sim 60$), and in-depth interviews ($N = 15$). Each of these is described in more detail below. Course artifacts were collected over five semesters and interview data were collected over the final four semesters. These *N*'s, as well as those reported throughout the paper, are totaled over all semesters unless otherwise indicated. The number of responses can differ across questions for a variety of reasons, including: not every exam question was asked every semester, not every student turned in every assignment, and there was some attrition over the course of each semester. The number of responses for each question will be presented in the appropriate data tables in each section below.

In the first week of class each semester, students were assigned to write 2–3 page homework essays that address their ideas about the physical size and structure of the Universe, how the Universe changes over time, and how humans fit into the big picture. We refer to these as pre-course homework essays. The assignment provided guiding questions, but the students were not required to respond to all of them. Students were urged to describe what they really thought and were graded on completeness only, not the accuracy of their work. The section of the assignment relevant to the Big Bang Theory, the expanding Universe, the age of the Universe, and the history of the Universe prompted students as follows:

> "Describe the Universe. (What do you think the Universe is like and how do you know?) Describe how you think the Universe changes over time, if at all. (For example, has the universe existed forever, or if not, how old is it? How do the ages of the Earth and Sun compare to the age of the Universe? To the ages of other stars? What laws guide the processes that happen? Where did everything in the Universe come from? How did things come to be the way they are now? Do objects in the Universe move around and if so, how?)"

These pre-course homework essays provide us with information on students' pre-instruction ideas. Since students were not required to specifically address each guiding question, but rather just the major themes, all response numbers obtained for the pre-course homework essays should be taken as lower limits (i.e., it is possible that more students hold a given idea but did not discuss it specifically in their essays). Also, because the students chose which topics to address in their pre-course homework essays, the number of essay responses on a given topic differs. In our tables and figures, we note the number of pre-course homework essay responses with information relevant to each question.

Other class data included three midterm exams and one final exam. Exam questions included long-format open-response (essay) questions and short-format questions taken from various sources, such as textbook question banks and questions created by our group or other ASTRO 101 instructors who have shared their materials with us. Short-format exam questions included matching and ranking questions, multiple-choice (MC), true-false (T/F), and fill-in-the-blank (FIB). The topics addressed in this article were only covered in the third midterm exam (hereafter, Exam 3) and the final exam.

The interviews were semi-structured, lasted between 30 and 40 min each, were recorded, and were transcribed afterward. Semistructured interviews are used when the researcher anticipates that questions will require discussion and possibly follow-up questions (Rubin and Rubin 2005). Our main questions were based on those in the Bailey *et al.* (2012) pre-course surveys. However, all interviewees were not asked all of the main questions. The purpose of a semi-structured interview is to allow the interviewee's responses to guide the interview and to use questions to get "a conversation going on a subject and ensure that the overall subject is covered" (Rubin and Rubin 2005, p. 13). In our tables and figures, we note the number of interviewees asked each question. Interviews took place throughout the latter half of each of four semesters. Thus, we are able to examine student ideas throughout the learning process. We use quotes and themes from the interviews as illustrative examples of the student ideas we gathered through our other course artifacts.

2.3. Data Analysis Procedure

We used a mixed methods approach in analyzing our data. For the pre-course homework essays, exam essay questions, and interviews, we carried out an iterative process of thematic coding to generate a comprehensive list of themes. We then identified the fraction of students who discussed a given theme in their response. For the exam essay questions, we also coded the responses for degree of completeness and correctness, by comparing the actual response to the desired response (which may contain more than one element). Correct answers are provided with the questions in the appropriate data analysis tables in the Appendix. In brief, we coded the responses as to whether they were correct "C," incomplete "I," partial "P," wrong "W," true but irrelevant "T," or non-scientific "NS." "C" refers to responses that contain all the correct elements of the answer. "I" refers to responses with at least one correct element, but missing some of the elements that constitute a fully correct answer. "P" refers to responses with both correct and incorrect elements. "W" refers to responses with only incorrect elements. "T" refers to responses that included statements that were true but did not address the question in any meaningful way. We marked a response as a no-response, “NR,” if the student left the question blank.

We used the Kruskal-Wallis (KW) test to determine whether we could aggregate results from different semesters. The KW test is a non-parametric method for testing the hypothesis that three or more sample populations (in our case, results from each semester) have the same mean distribution, against the hypothesis that they differ (Note-6) (Nussbaum, private communication). One advantage of the KW test is that it is applicable to data sets in which the number of values from each semester are of equal or unequal lengths (i.e., it is valid even if there are different numbers of students in each semester). Here, we used a conservative significance level of 0.1. If our p-value is greater than 0.1, we do not reject the null hypothesis that the semester results come from the same parent population. In other words, $p > 0.1$ means we can use the aggregated results because the semesters do not appear to differ significantly from one another. For each question, we ran a KW test to determine whether the different semesters’ data could be combined. In all but one case, the p-value was greater than 0.1, so we were able to aggregate results across semesters. It is the aggregated data that are reported below. For the one result that cannot be aggregated (Table 4.3), we make a note of this in the text and refer to the individual semester results instead.

We used a Kolmogorov-Smirnov (KS) test for questions where there were only two semesters to combine (Conover 1999). The KS test is also a non-parametric method and we use the same conservative significance level of 0.1 to determine whether the two semesters’ results can be aggregated. In all cases, the p-value was greater than 0.1, so we were able to aggregate results across semesters.

In order to not interrupt the flow of the analysis, we provide individual semester results for the exam T/F, FIB, MC, and essay questions in table form in the Appendix, including the KW H-statistic (or KS statistic, when appropriate) and the p-value for each. In the body of the text, we provide tables and figures with the aggregate results.

In each section below, the results of the course artifacts are presented in chronological order (pre-course homework essays, midterm exams, and final exams). This creates a coherent narrative of student ideas over the course of the learning process. This sometimes limits the physical proximity of matched data, but better elucidates what students are thinking as they acquire new knowledge. A short description of the curriculum is given as context for the environment in which the development of student ideas is taking place. However, discussions of the curriculum will be kept brief, as it is not our intention in this study to measure its effectiveness

3. BIG BANG THEORY

The Big Bang Theory is the prevailing theory for the evolution of our Universe. The model, based on available evidence, proposes that there was an event in which space and time appeared, that the early Universe was very hot and very dense, and that space itself has since expanded and the Universe has cooled. There are several pieces of observational evidence in support of the Big Bang Theory: (1) we observe that the Universe is expanding, (2) the composition of atoms is consistent with the theory (Note-7), and (3) the Cosmic Microwave Background (CMB) exhibits a nearly uniform temperature across the sky, whose perturbations indicate over- and under-densities that led to the large scale structure we see today.

Students engage in learning about the Big Bang Theory through a mini-lecture early in the course and in more depth later in the course through the *Lecture-Tutorials* “Making Sense of the Universe” and “The Big Bang” (Wallace, Prather, and Duncan 2012b). In the first tutorial, the students examine a schematic of our galaxy’s observable Universe and consider the properties of the observable Universe for a galaxy at the edge. They then deconstruct statements within a mock dialogue between two students discussing their understanding of our observable Universe. In the second tutorial, the students first compare and contrast two representations for the expansion of the Universe and deconstruct the statements within a mock dialogue between two students debating their responses. The students then investigate how the density, energy, and temperature of the Universe evolve over time, using simple representations as a guide. The tutorial then leads them through the thought experiment of playing the movie of the history of the Universe in reverse, drawing conclusions about the implications for the early Universe. Finally, the students again deconstruct the statements within a mock dialogue between three students discussing their understanding of the Big Bang Theory.

We have divided student ideas about the Big Bang Theory into five subsections to help guide the reader. In Section 3.1, we present student ideas with regard to the creation aspect of the Big Bang Theory. In Sections 3.2, 3.3, and 3.4, respectively, we discuss student ideas about the conditions in the early Universe, whether the “Big Bang” refers to an explosion, and whether the Universe has a center. In Section 3.5, we describe student ideas on observational evidence in support of the Big Bang Theory.

A number of tables and figures are relevant across Sections 3.1–3.4. We briefly describe the data here and present the tables and figures in a series below. Figure 3.1 provides the results for the 26 students who discussed the Big Bang Theory in their pre-course homework essay. Figures 3.2 and 3.3 summarize the results from our interviews conducted prior to and after detailed instruction, respectively, on this topic. Students also responded to an essay question on Exam 3 and the Final Exam, “Describe the Big Bang Theory” [see Table 3.1 and Figures 3.4(a) and 3.4(b)].

3.1. Creation

3.1.1. Results

Of the students in our study who mentioned the Big Bang Theory in their pre-course homework essays, 77% (20 of 26) refer to it as describing the creation of the Universe and 8% (2 of 26) refer to it as describing the creation of planets and/or our Solar System (Figure 3.1). Because the pre-course homework essays are free-form responses and students were not required to address any particular concept or topic, this likely represents a lower limit to the fraction of students who hold the latter view. In the interviews that occurred before in-depth instruction, 80% of students (4 of 5) spoke of the Big Bang Theory as a description of the formation of the Universe and 20% of students (1 of 5) attributed to it the formation of our Solar System (Figure 3.2).

Only 1 student of 43 (2%) and 2 students of 45 (4%) on Exam 3 and the Final Exam, respectively, referred to the creation of planets or our Solar System when describing the Big Bang Theory [Figures 3.4(a) and 3.4(b)]. In our interviews that occurred after in-depth instruction (Figure 3.3), three of the five students referred to the creation of the Universe in describing the Big Bang Theory. One interviewee, on the other hand, specifically did not attribute the formation of the Universe to the “Big Bang” because s/he strongly believes the Universe to be timeless, and so no particular event could be responsible for its creation. We discuss this alternate conception further in Section 5.

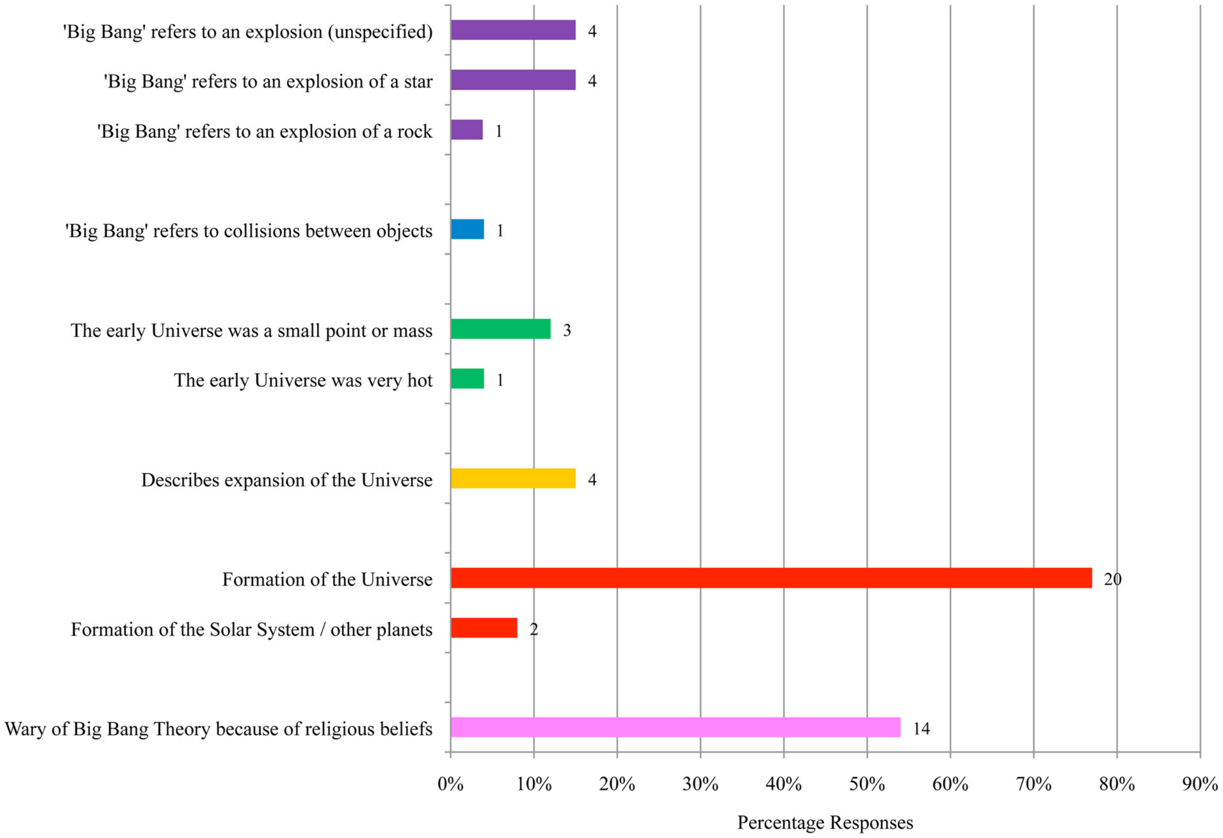


Figure 3.1. Pre-course Homework Essay. Thematic Coding. References to the Big Bang Theory, $N = 26$

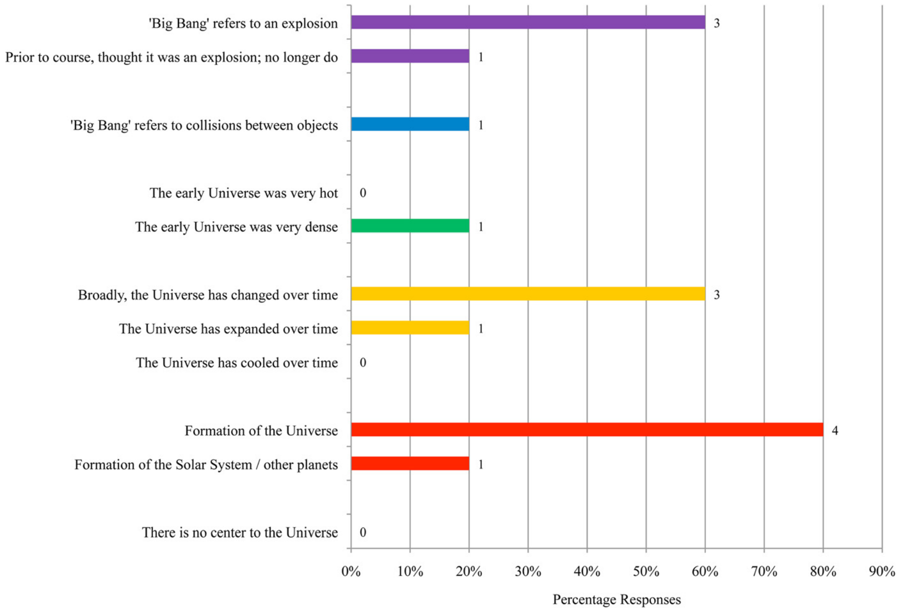


Figure 3.2. Interviews Prior to In-Depth Instruction. Thematic Coding.
Q: Describe the Big Bang Theory, $N = 5$

3.1.2. *Implications*

In teaching about the Big Bang Theory, it is important for educators to be mindful that a notable fraction of their students come in to their course believing the Big Bang Theory describes events that immediately led to the creation of stars, planets, Earth, or more generally our Solar System. As noted in the literature, this has been documented with the following percentages: 27%, Bailey *et al.* (2012); 25%, Prather, Slater, and Offerdahl (2002);

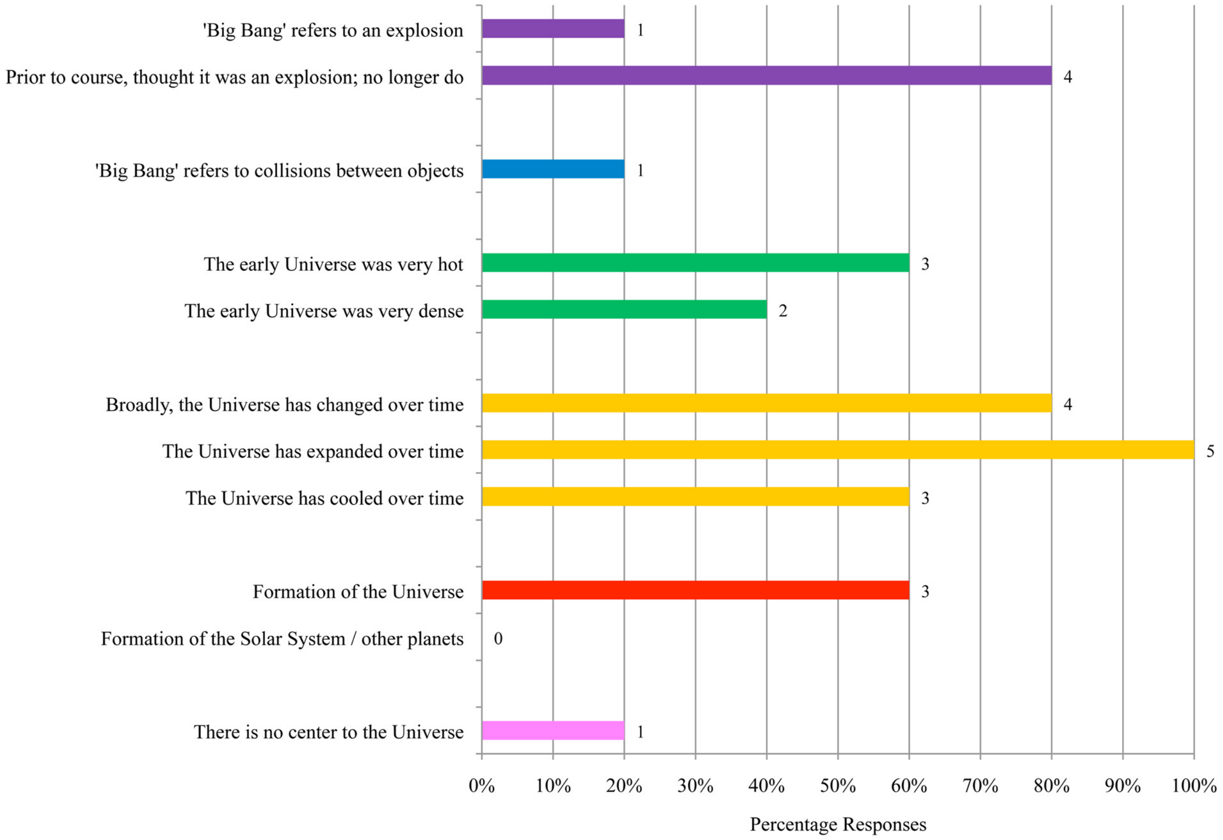


Figure 3.3. Interviews Prior to In-Depth Instruction. Thematic Coding.
Q: Evidence for the Big Bang Theory, $N = 5$

Table 3.1. Exams Essay Question. Aggregate Results
Q: Describe the Big Bang Model (Note-8).

Exam 3 (*N* = 43):

C	I	P	W	T	NR	NS
17%	48%	17%	14%	0%	5%	0%

Final Exam (*N* = 45):

C	I	P	W	T	NR	NS
11%	69%	9%	11%	0%	0%	0%

25%, Simonelli and Pilachowski (2003); 10–22%, Wallace, Prather, and Duncan (2012a); and, in this study, at least 8%.

One factor that may contribute to students' misattributing the creation of our Solar System to the Big Bang Theory is their misuse of the terms "Solar System," "Galaxy," and "Universe" and not having a clear sense of how the terms relate to one another. For example, in responding to the pre-course homework essay questions about the Big Bang Theory, students may in fact be correctly thinking that "the Big Bang Theory describes the creation of the Universe" in their incorrect phrasing "the Big Bang Theory describes the creation of the Solar System." In Coble *et al*. (Paper I, 2013) and Bailey *et al*. (2012), we discuss this misuse of terminology in more detail.

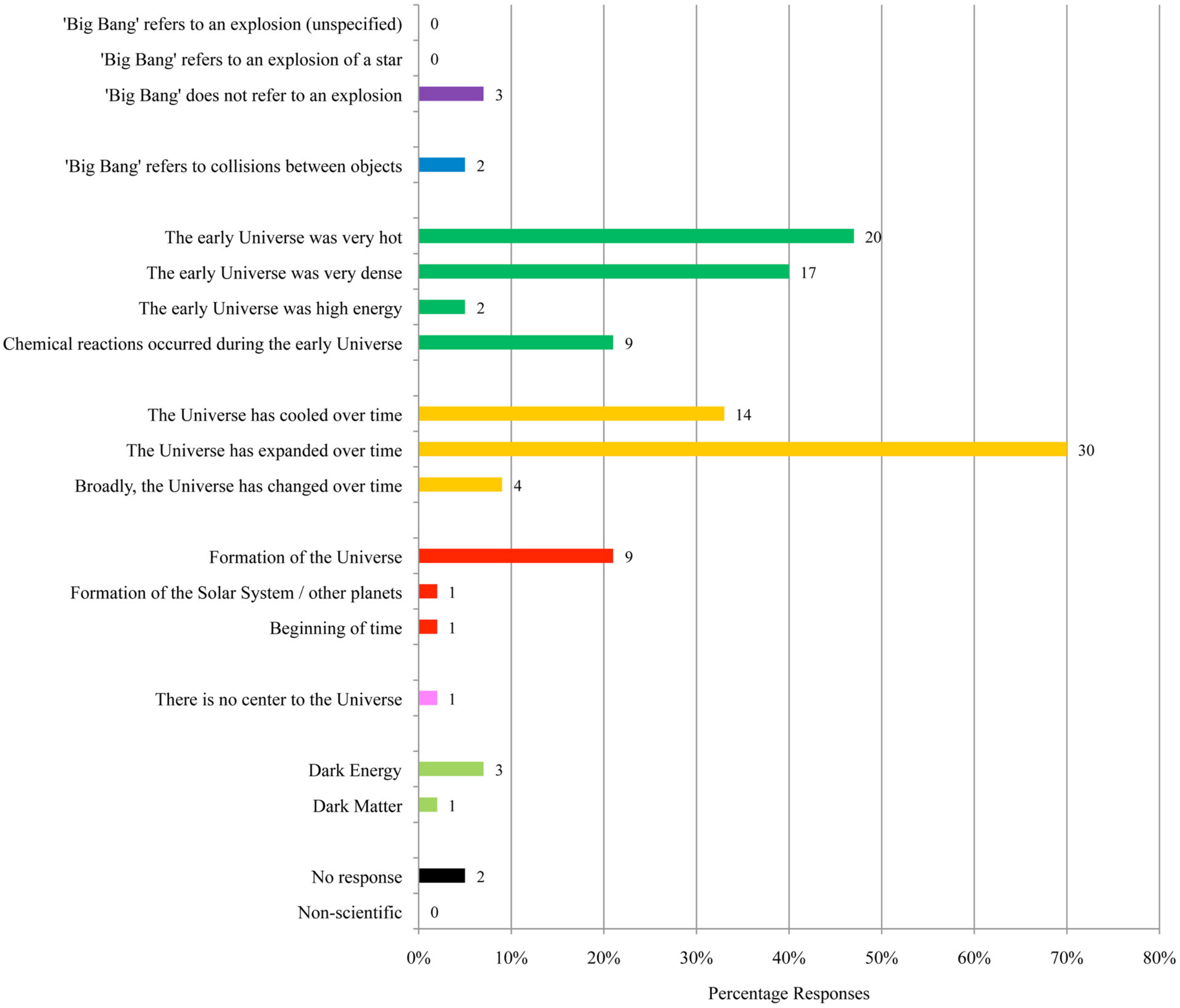


Figure 3.4a. Exam 3. Essay Question. Thematic Coding.
Q: Describe the Big Bang Model, *N* = 43

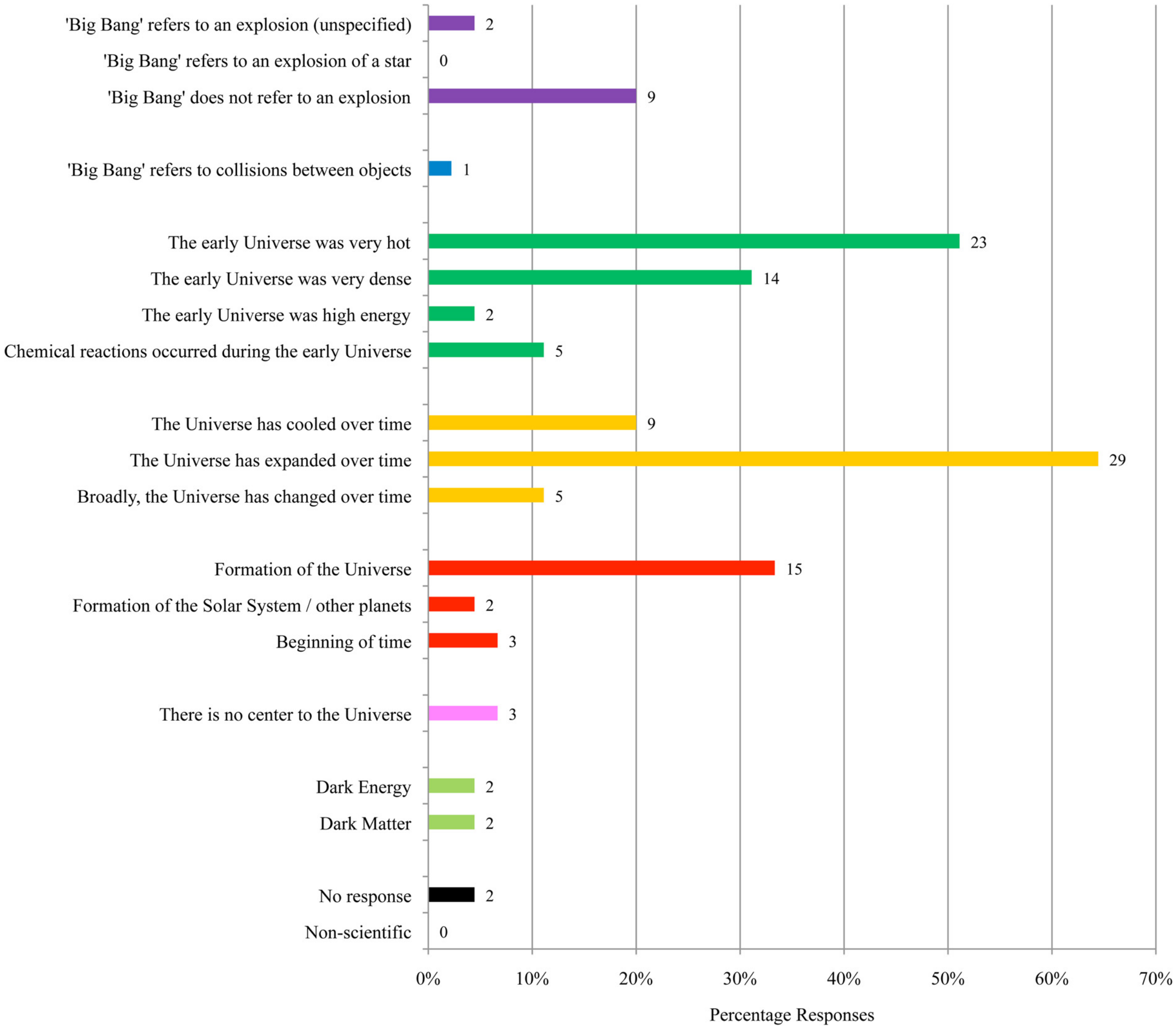


Figure 3.4b. Final Exam. Essay Question. Thematic Coding.
Q: Describe the Big Bang Model, $N = 45$

Simonelli and Pilachoswki (2003) hypothesize that another factor is student misunderstanding of cosmic history. If students had a clearer timeline of the "Big Bang" occurring 13.7 billion years ago and our Solar System forming 9 billion years later, they would be less likely to attribute the formation of our Solar System directly to the Big Bang Theory. In Section 6 of this article, we discuss how, even after in-depth instruction, a notable fraction of students persist in holding the alternate conception that the formation of stars, galaxies, and our Solar System occurred much earlier in cosmological time than in reality.

3.2. Conditions in the Early Universe

3.2.1. Results

Only one student in the pre-course homework essay and no students in the interviews that occurred prior to in-depth instruction mentioned that the early Universe was very hot. Furthermore, no students in the pre-course homework essays and only one student in the interviews that occurred prior to in-depth instruction discussed density (Figures 3.1 and 3.2).

On the other hand, in response to the exam essay question, "Describe the Big Bang Theory," 47% of students (20 of 43) on Exam 3 and 51% of students (23 of 45) on the Final Exam referred to the early Universe as being very hot. A notable fraction of students, 33% (14 of 43) on Exam 3 and 20% (9 of 45) on the Final Exam, described the subsequent cooling of the Universe over time in response to this exam essay question [Figures 3.4(a) and 3.4(b)]. Three of the five students (60%) interviewed after in-depth instruction discussed both the high temperature in the early Universe and subsequent cooling when describing the Big Bang Theory (Figure 3.3).

For example, Interview H explained, "[The Big Bang] is saying that at one time our Universe was hot and dense and over time… space expands… it becomes cooler."

In response to the exam essay question, "Describe the Big Bang Theory," only 17% of students (7 of 42) on Exam 3 and 11% of students (5 of 45) on the Final Exam were fully correct (Table 3.1). A major factor in receiving an "Incomplete" was failing to mention that the Universe has been cooling over time; 38% of students (16 of 42) on Exam 3 and 44% of students (20 of 45) on the Final Exam received an "Incomplete" at least in part for this reason.

3.2.2. Implications

In the CSU course, the decrease in temperature with time is discussed during the mini-lecture, but is not emphasized in any active learning activity (although it is briefly mentioned in the "Big Bang" *Lecture-Tutorial*). So while we found that a notable fraction of students after in-depth instruction *do* refer to the early Universe as being very hot and that it cools over time, it is clear that these aspects need to be further emphasized so that a larger fraction of students incorporate them into their frameworks.

Wallace, Prather, and Duncan (2012a) pointed out a key factor that could lead to confusion and difficulty in learning this concept. They found a relatively even distribution of student pre-instructional ideas with regard to how the temperature of the Universe changes over time (increasing, 18–42%; decreasing, 25–40%; and constant, 30–35%; see their Figure 2). Most importantly, they found that if the student does think the temperature changes over time, s/he attributed this change to the birth and death of planets, stars, and galaxies, not to any cosmologically significant change. Typically students learn about stellar processes before learning about the Big Bang Theory and the expansion and cooling of the Universe. It is essential that instructors take the time to support students in making the distinction between stellar processes heating and cooling the interstellar medium on relatively local scales (with an insignificant impact on cosmological scales), and the long-term cooling spanning the large distance scales of the Universe.

3.3. Confusing the "Big Bang" with an Explosion

3.3.1. Results

Of the students in our study who discussed the Big Bang Theory in their pre-course homework essays, 31% (8 of 26) referred to the "Big Bang" as an explosion (Figure 3.1). Four of the students attributed this explosion to a star exploding, one attributed it to a rock exploding, and four did not specify what explodes. For example, one student wrote, "The Universe is created by stars blowing up." Another wrote, "The Universe formed as a result of a star that exploded and over time formed many systems and made what is known as planets, galaxies, solar systems, and other planetary formations such as mountains, rivers, and land structures." A third student wrote, "The Big Bang Theory, from what I have been taught in school, is the name of when a gigantic rock exploded, out of nowhere, and had atoms in it create everything from a grain of sand to a human being."

Similar ideas were expressed by three of the five students who participated in our interviews prior to in-depth instruction (Figure 3.2). Interview A described his/her view of the early Universe as follows, "It was like a dense, hot ball and it got to the point where… I guess the bonds or something really couldn't hold it any longer, so it just exploded. And through the explosion, things just started moving further apart, like expanding…from where the explosion actually happened." This student also explained that s/he thinks about it "like if you had a bomb here on Earth". The 'bomb' visualization is strongly imprinted in students' mental model for the creation of our Universe. Interview B explained, "When I think of the "Big Bang"… it's like, okay, something went off, it exploded, and everything dispersed out. I need to have some kind of visual to explain how things work."

Almost all students (96%; 45 of 47) correctly responded to the T/F exam question about the Big Bang Theory referring to an explosion (Table 3.2). Furthermore, on the exam essay question "Describe the Big Bang Theory," none of the students on Exam 3 and only 4% of students (2 of 45) on the Final Exam refer to the "Big Bang" as an explosion [Figures 3.4(a) and 3.4(b)]. In our interviews after in-depth instruction, one of the five students still referred to the Big Bang Theory as an explosion (Figure 3.3).

Of the students who discussed the Big Bang Theory in their interviews after in-depth instruction (Figure 3.3), 80% (4 of 5) explicitly stated that while before taking the class they thought the "Big Bang" referred to an

Table 3.2. Exam 3. T/F. Aggregate Result. $N = 37$
Q: The Universe began with a giant explosion, like a bomb. True/**False.**

T	F
4%	96%

explosion, they now knew that no explosion is involved. Visualizations we used in class (Note-9) seem to have helped replace their alternate conception with a more scientifically accurate view, as expressed by two quotes from the student interviews. Interview N stated, "What [...] helped me learn it [that an explosion does not describe the 'Big Bang'] and get a better understanding of it was that whole movie going backwards in time." Interview O noted, "I learned from the class the "Big Bang" was not that concept [an explosion]… That the "Big Bang" is really not a big bang, it's really a big stretch [referring to the stretchy band used in class to demonstrate the expanding Universe]." Both of these visualizations negate the need for an explosion as part of students' mental picture for the creation of our Universe.

3.3.2. *Implications*

Bailey *et al*. (2012) found that 51% of students in pre-course surveys state that the 'Big Bang' refers to an explosion, with 6% specifying that it is an exploding star and 45% not specifying what explodes. Similarly, Wallace, Prather, and Duncan (2012a) and Prather, Slater, and Offerdahl (2002) found, respectively, that 52–56% and ~44% of students describe the 'Big Bang' as an explosion in their pre-course surveys. Our results are lower (24%) likely because we do not require students to discuss this aspect of the Big Bang Theory in their pre-course homework essays, so our percentage should be taken as a lower limit.

The prevalence of this alternate conception is not surprising given the misleading terminology "Big Bang" and its common portrayal in the news, in K-12 education, and in museums. For example, the Harvard Center for Astrophysics docent guide for their "Cosmic Questions" exhibit (Note-10) states: "[In] the Big Bang model, the entire contents of the Universe expanded explosively into existence from a single, hot, dense chaotic mass, and continues to expand today" (p. 44). And this is among the better descriptions provided to the public.

Exam questions that do not address this alternate conception directly can mislead instructors into thinking that it is easily overcome by simply stating in lecture that the Big Bang Theory does not describe an explosion that sets off the creation of our Universe. We found that almost all students correctly responded to the T/F question and avoided use of the term "explosion" in their exam essay response. However, when we probe student understanding more deeply, it appears that this alternate conception can be difficult to overcome, as evidenced by statements referring to the "Big Bang" as an explosion in the interviews that occurred after in-depth instruction.

3.4. Is there a Center to the Universe?

3.4.1. *Results*

None of the students discussed in their pre-course homework essays whether the Universe has a center or not. Post in-depth instruction, almost all (96%; 42 of 44) students correctly responded to the exam MC question that the Universe does not have a center (Table 3.3). Furthermore, one student in his/her Exam 3 response and three students in their Final Exam response to the essay question "Describe the Big Bang Theory," plus one of five

Table 3.3. Final Exam. Aggregate Result. $N = 44$
Q: According to modern ideas and observations, what can be said about the location of the center of our expanding universe?

a. The earth is at the center
b. The Sun is at the center
c. The Milky Way Galaxy is at the center
d. **The Universe does not have a center**

A	B	C	D
2%	0%	2%	96%

students in the interviews that occurred after in-depth instruction, made the unsolicited statement that the Universe has no center (Table 3.3 and Figure 3.3).

A more complex, but related alternate conception is the idea that the Universe began as a small point or mass. A notable fraction, 12% (3 of 26), of students who discussed the Big Bang Theory in their pre-course homework essay stated this incorrect visualization (Figure 3.1). Because we did not require students to discuss this, 12% likely represents a lower limit to the number of students who held this view prior to instruction.

Only one student on Exam 3 and one student on the Final Exam essay question "Describe the Big Bang Theory" incorrectly referred to the early Universe as a small, single point [Figures 3.4(a) and 3.4(b)]. We assume that this is a lower limit to the total number of students who held this view, since the exam question did not explicitly request the students' understanding of this aspect of the Big Bang Theory. No exam question or interview question followed-up directly on this aspect of student understanding.

3.4.2. Implications

Trumper (2000), Kalkan and Kiroglu (2007), and Wallace, Prather, and Duncan (2012a) found that 27%, 35%, and 7–30% of students, respectively, state that the Universe has a center prior to instruction. Kalkan and Kiroglu (2007) also conducted a post-instruction test in their study of 100 preservice elementary school teachers. The rate of incorrect responses decreased to 12%. They found that for the fraction of students who came into the course with the alternate conception that the Universe does have a center, it was a relatively easy concept to replace, even with limited instructional effort. Our exam results corroborate their finding (e.g., almost all students responding correctly to a MC question on this topic).

Related to the pre-instruction alternate conception that the Universe has a center is that the Universe began within a small point in space, or within a small mass. In Bailey *et al.* (2012), 13% of students include this in their pre-instruction description of the Big Bang Theory. We find that 12% of students expressed this view in their pre-course homework essays, but only two students explicitly included this view in their exam responses. We did not probe this question in particular in our interviews that occurred after in-depth instruction. It would be interesting to examine this in more detail in a future study, particularly to investigate how students reconcile their alternate conception that the "Big Bang" occurs within a small, single point in space with their correct conceptions that there is no center to the Universe.

3.5. Observational Evidence in Support of the Big Bang Theory

None of the students in their pre-course homework essays discussed evidence in support of the Big Bang Theory. All ten students interviewed before and after in-depth instruction on the Big Bang Theory were asked about their ideas on observational evidence for the theory (Figures 3.5 and 3.6). Students also responded to an essay question on Exam 3 and the Final Exam, "Provide 2 pieces of observational evidence for the Big Bang Theory" [Table 3.4 and Figures 3.7(a) and 3.7(b)].

3.5.1. Results

While we do not explicitly require students to discuss evidence for the Big Bang Theory in their pre-course homework essay, it is interesting to note that not a single student touched on this subject. In the interviews that occurred prior to in-depth instruction, 60% of students (3 of 5) stated that they did not know of any evidence supporting the Big Bang Theory. The two students who did know of evidence mentioned both the expansion of the Universe and the composition of the Universe. One of the two students stated that the CMB can be used, but was unable to explain why (Figure 3.5).

In response to the Exam 3 essay question, "Provide two pieces of observational evidence for the Big Bang Theory," 23% (7 of 30) were correct (combining the responses which provided an explanation and those that just listed the term CMB without explanation), 20% (6 of 30) were "Incomplete," 20% (6 of 30) were "Wrong," and 17% (5 of 30) left the question blank. On the Final Exam for this same essay question, the fraction of students who were correct was similar, 21% (4 of 19). A higher fraction, 37% (7 of 19), were "Incomplete," and the

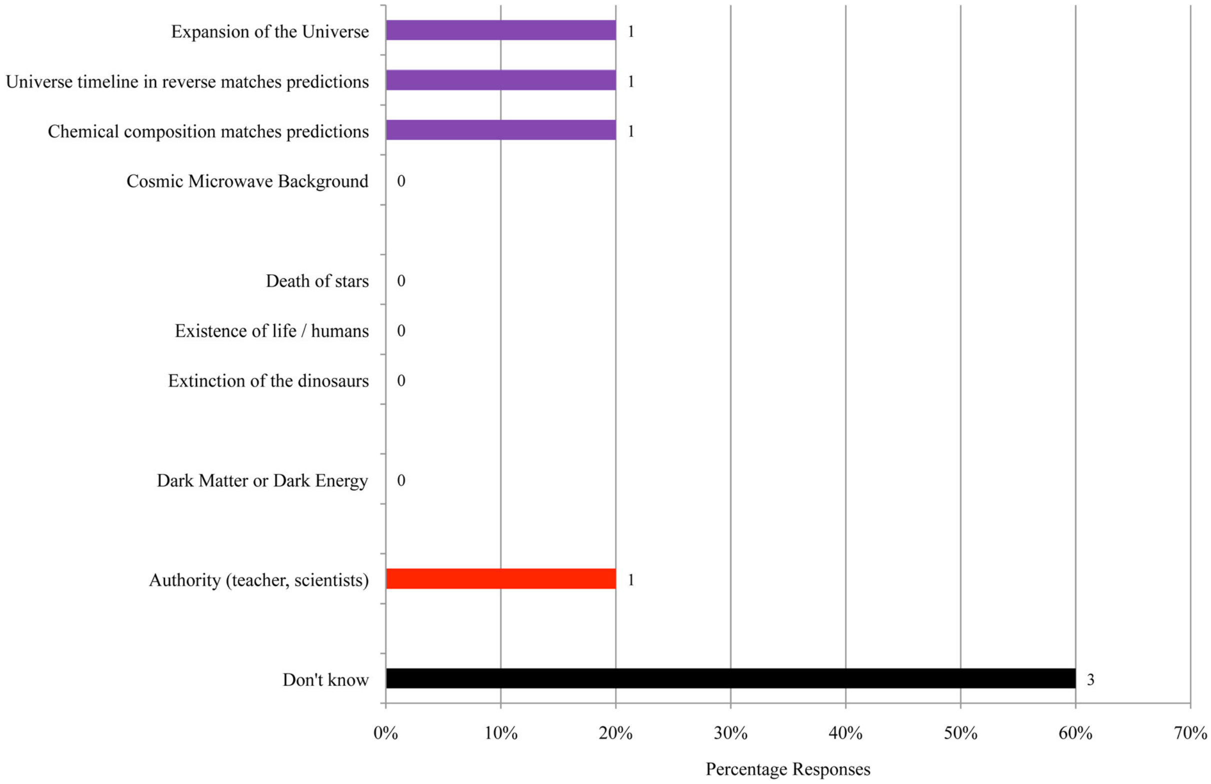


Figure 3.5. Interviews After In-Depth Instruction. Thematic Coding.
Q: Describe the Big Bang Theory, $N = 5$

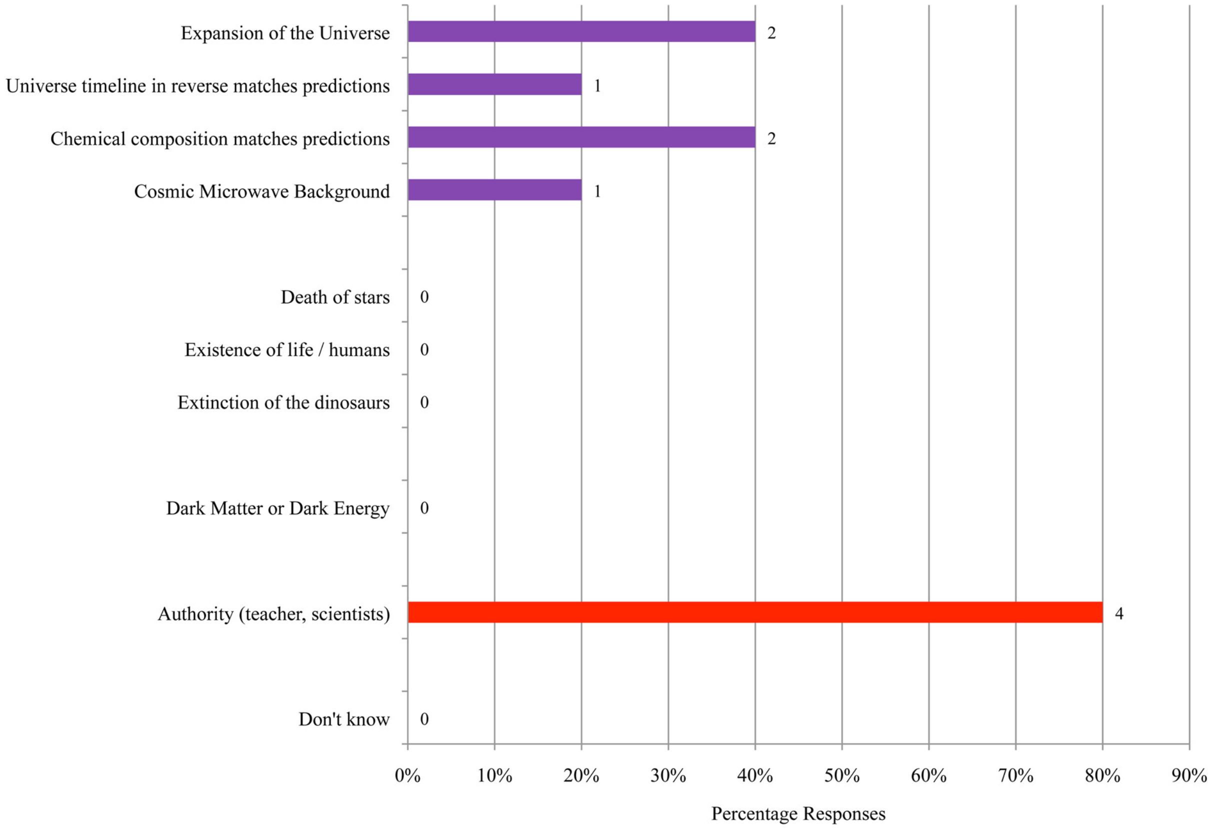


Figure 3.6. Interviews After In-Depth Instruction. Thematic Coding.
Q: Evidence for the Big Bang Theory, $N = 5$

Table 3.4. Exams. Essay Question. Aggregate Results

Q: Describe two pieces of observational evidence for the Big Bang Model.

Note: if they only listed the term "CMB," but included no description, we placed the response within the appropriate "-L" (for "list") category.

Exam 3 ($N = 30$):

C	I	P	W	T	C-L	I-L	P-L	NR	NS
3%	13%	17%	20%	0%	20%	7%	3%	17%	0%

Final Exam ($N = 19$):

C	I	P	W	T	C-L	I-L	P-L	NR	NS
5%	16%	10%	5%	0%	16%	21%	5%	21%	0%

fraction that were "Wrong" decreased to only 5%. There was still a notable fraction, 21% (4 of 19), who left the question blank (Table 3.4).

In the interviews that occurred after in-depth instruction, all of the students (5 of 5) who were asked about evidence for the Big Bang Theory provided at least one form of observational evidence (Figure 3.6). None of the students in the exam responses or in the interviews that occurred after in-depth instruction explicitly stated that there is no evidence for the Big Bang Theory.

The most commonly cited observational evidence in response to the exam essay question and in interviews was that the Universe is expanding: 47% of students (14 of 30) on Exam 3 (Figure 3.7(a)), 50% of students (10 of 20) on the Final Exam [Figure 3.7(b)], and 40% of students (2 of 5) in our interviews after in-depth instruction cited this observation (Figure 3.6).

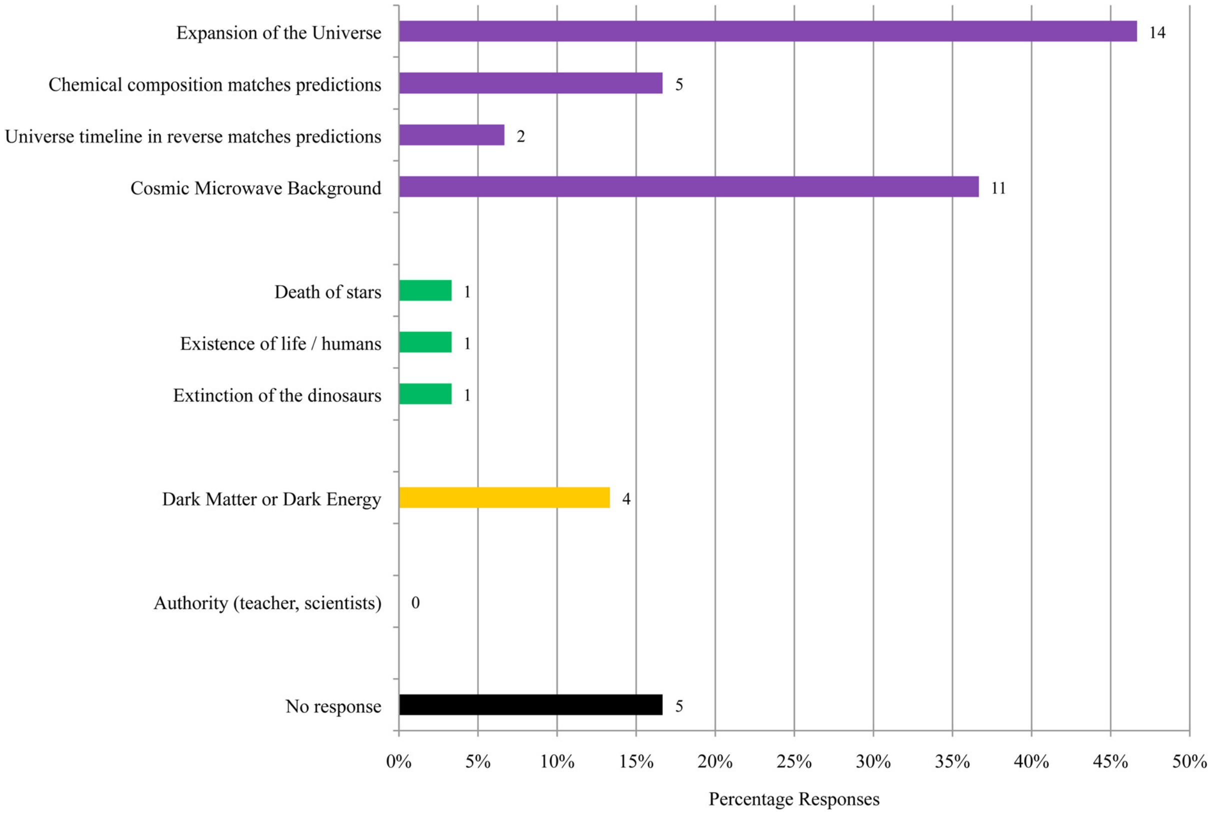


Figure 3.7a. Exam 3. Essay Question. Thematic Coding.
Q: Describe two pieces of observational evidence for the Big Bang Model, $N = 30$

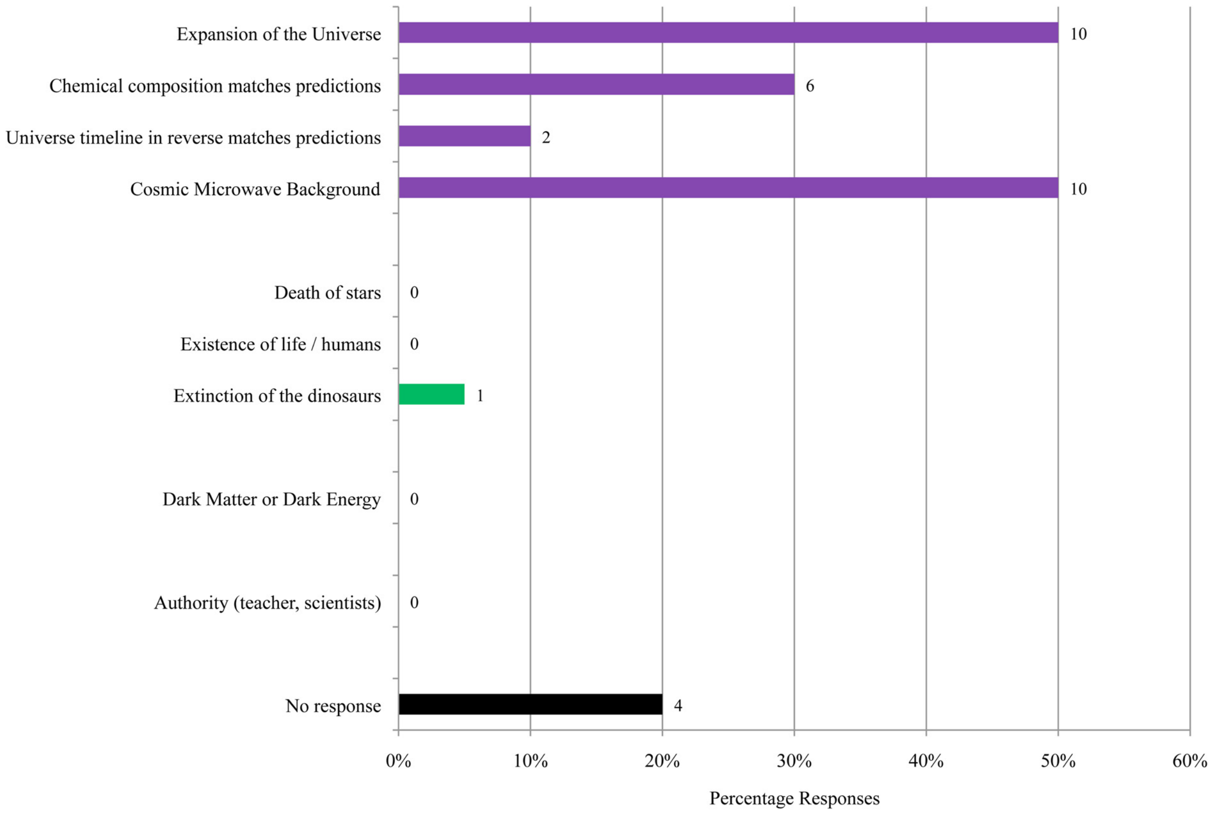


Figure 3.7b. Final Exam. Essay Question. Thematic Coding.
Q: Describe two pieces of observational evidence for the Big Bang Model, $N = 20$

Related to the idea that the expansion of the Universe provides evidence in support of the Big Bang Theory is that scientists can run simulations of the history of the Universe in reverse to recreate the conditions for the early Universe, for which the Big Bang Theory has made predictions. In Exam 3 responses, Final Exam responses, and interviews, 7%, 10%, and 20% of students, respectively, describe this aspect (Figures 3.7(a)–3.6).

The next most common response provided after in-depth instruction was the CMB, with 37% of students (11 of 30) on Exam 3, 50% of students (10 of 20) on the Final Exam, and 20% of students (1 of 5) in interviews listing this as evidence for the Big Bang Theory (Figures 3.7(a), 3.7(b)–3.6, respectively). However, it is important to note that in the Exam 3 and Final Exam responses, only one student provides a correct description of the CMB, while the remainder simply listed the term or provided an incorrect description. The student who discussed the CMB in an interview after in-depth instruction occurred (Interview H) frankly stated, "I won't even try to explain it because I'm not sure."

The final correct response that students provided for this question after in-depth instruction is that the chemical composition of our Universe corresponds to predictions from the Big Bang Theory and subsequent stellar evolution. In Exam 3 responses, Final Exam responses, and interviews after in-depth instruction, 17% of students (5 of 30), 30% of students (6 of 20), and 40% of students (2 of 5), respectively, describe this aspect (Figures 3.7(a), 3.7(b)–3.6).

There was only one student on Exam 3 and no students on the Final Exam who incorrectly discussed the death of stars as evidence for the Big Bang Theory. One student on Exam 3 and one student on the Final Exam referred to the extinction of dinosaurs and one student on Exam 3 referred to life on Earth as evidence for the Big Bang Theory [Figures 3.7(a) and 3.7(b)]. Finally, 13% of students (4 of 30) incorrectly brought up dark energy and/or dark matter as evidence for the Big Bang Theory in their Exam 3 responses [Figure 3.7(a)]. No students did this on the Final Exam or in our interviews that occurred after in-depth instruction.

3.5.2. Implications

Our interview results suggest that prior to in-depth instruction, the majority of students do not know of any evidence supporting the Big Bang Theory. Bailey *et al.* (2012) found that 38% of students in their pre-course surveys did not know of any evidence for the Big Bang Theory. While we find that this fraction decreases as the course progresses, a notable fraction remained (approximately one-fifth of students on Exam 3 and the Final Exam left this essay question blank).

It is important to note that ‘I don’t know’ is a significantly different answer than ‘There is no evidence for the Big Bang Theory’. In the pre-course surveys, Bailey *et al.* (2012) found that 5% of students explicitly stated that they believed there is no evidence for the Big Bang Theory. None of the students in our exam responses or in our interviews that occurred after in-depth instruction explicitly stated that they believed there is no evidence for the Big Bang Theory. However, because the wording of the questions on the pre-course surveys (‘Describe what evidence you think supports the Big Bang Theory?’), exams (‘Describe 2 pieces of evidence for the Big Bang Theory’), and interviews (‘What evidence is there for the Big Bang Theory’) pre-supposes the existence of evidence, this may suggest to students that they should respond that they do not know of evidence, rather than stating they think there is no evidence, if that is in fact the case. It would be interesting to conduct a follow-up study on this point.

Bailey *et al.* (2012) found that 14% of students in pre-course surveys offered the expansion of the Universe as evidence in support of the Big Bang Theory. We find that this is also the most common response given in exams and interviews that occurred after in-depth instruction (47% of Exam 3 essay responses, 50% of Final Exam essay responses, and 40% of interviews). No students in the pre-course survey listed the CMB or chemical composition (Bailey *et al.* 2012), while a notable fraction of students referred to these as evidence in their exam responses and interviews that occurred after in-depth instruction (20%–50%). However, it is important to note that only one student in our study was able to give a correct explanation for why the CMB is evidence in support of the Big Bang Theory. Given that we only discuss the CMB as evidence in support of the Big Bang Theory in our mini-lecture, it is not surprising that the students do not have a stronger understanding of this rather complex concept.

Bailey *et al.* (2012) also identified a number of pre-course alternate conceptions for what constitutes evidence for the Big Bang Theory, including the existence of the Solar System (9%), the existence of life (6%), and the extinction of dinosaurs (5%). We found that either one or no students persisted in adhering to these alternate conceptions after in-depth instruction. These learning gains are promising, however, again, the fact that only 21% of students are fully correct in their response to the Final Exam essay question on this topic indicates that this may be a difficult concept to learn.

Instructors should also note that once students learn about dark matter and dark energy, they may be prone to incorrectly associating these complex concepts with evidence for the Big Bang Theory. For example, while no students cited dark matter or dark energy as evidence for the Big Bang Theory in the pre-course surveys in Bailey *et al.* (2012), we find that 13% of students (4 out of 30) incorrectly referred to dark energy and/or dark matter as evidence for the Big Bang Theory in their Exam 3 responses.

4. EXPANSION OF THE UNIVERSE

A consequence of the Big Bang Theory is that we live in an expanding Universe, in which the space between galaxies is expanding. Hubble’s Law (also know as LeMaitre’s Law) states that a galaxy’s recessional velocity is proportional to its distance from the observer ($v = H_0 d$), where the constant of proportionality (H_0) has been labeled Hubble’s constant. In other words, the farther the galaxy, the faster it is moving away from us. Hubble’s Law is the direct physical observation of the expanding Universe. On small scales, gravity overcomes this expansion such that planets orbit their star, stars move under the gravitational influence of their host galaxy, and galaxies move toward the nodes (clusters of galaxies) within the large-scale filamentary structure.

Students engage in understanding and measuring the expansion rate of the Universe in the second half of the course through a mini-lecture and group practice problems on Doppler shift, a mini-lecture on the Hubble Law, interacting with a stretchy spandex band with galaxies stapled to it to demonstrate the space expanding between galaxies, manipulation of the Mastering Astronomy raisin bread applet, a video showing the expansion of the Universe in reverse, the *Lecture-Tutorial* ‘Expansion of the Universe’ (Adams, Prather, and Slater 2005), and a variation on the University of Washington Hubble Law lab (Larson *et al.*, n.d.). In this 2 h laboratory, the students use real data and the “standard ruler approach” to find the distances to galaxies, determine the redshifts of the galaxies from their spectral lines, calculate the expansion rate of the Universe, and calculate the age of the

Universe based on the expansion rate. The laboratory was modified to shift the focus from a verification-style laboratory to one in which students had to predict what they would observe and then test their predictions with the data. The data collection and analysis were trimmed to include fewer galaxies and only one spectral line, representative of the overall sample, so that students could focus on understanding the concepts as well as working hands-on with the data.

Of the 55 students who completed the pre-course homework essay, 34 (62%) discussed how the Universe evolves over time and whether objects move within our Universe (Figure 4.1). We asked three students about this topic in interviews prior to in-depth instruction (Figure 4.2). After in-depth instruction on this topic, we interviewed nine students about their ideas (Figure 4.3). Students also responded to a series of MC and FIB questions about the motion of galaxies in an expanding Universe (Tables 4.1–4.3).

4.1. Results

In their pre-course homework essays, 34 students addressed the evolution of the Universe and the movement of astronomical objects (Figure 4.1). Over half of the students (20 of 34) described the orbits of planets and/or moons in our Solar System. Fifteen students (41%) stated that the Universe is expanding. An additional eight (24%) stated that objects move, but did not specify in what way they move. For example, one student wrote, “Things move and evolve, just like we do.”

Of the eleven students who discussed the forces driving the movement of astronomical objects in their pre-course homework essays, six attributed their motion to gravity, one attributed their motion to magnetic fields, and four did not specify (Figure 4.1). Only one student in his/her pre-course homework essay expressed the belief that gravity does not exist in space. S/he wrote, “It is pretty cool just imagining how objects move through the Universe with no gravity as well as no friction.” Two of the three students who were asked about how the Universe has changed over time in interviews prior to in-depth instruction discussed the expansion of the Universe (Figure 4.2).

Almost all students (100% on Exam 3 and 96% on the Final Exam) correctly answered the MC question about galaxy motion as a result of the expansion of the Universe (Table 4.1). Furthermore, approximately 70% of

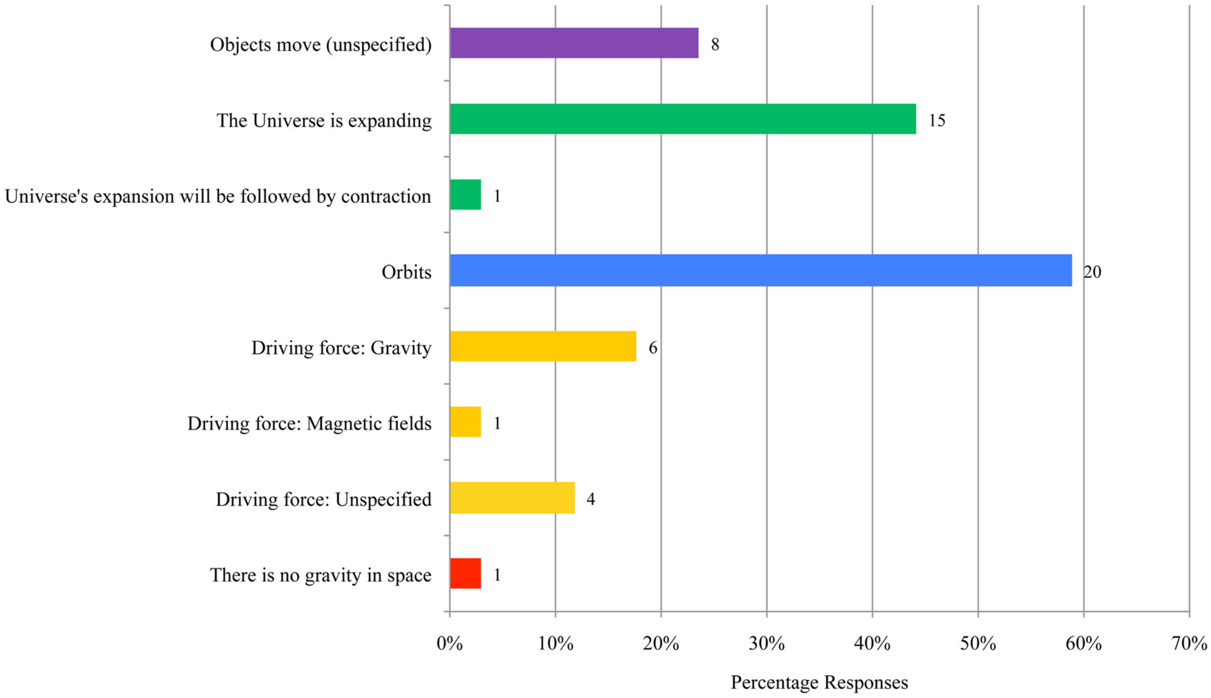


Figure 4.1. Pre-course Homework Essay. Thematic Coding.
Q: Describe how you think the Universe changes over time, if at all. (For example… Do objects in the Universe move around and if so, how?) $N = 34$

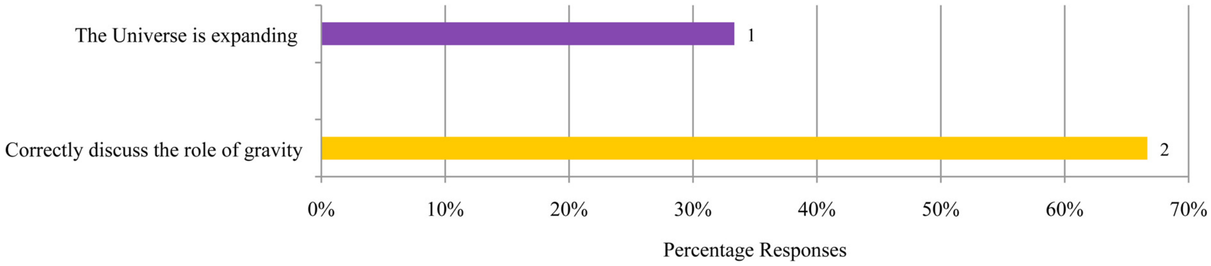


Figure 4.2. Interviews Prior to In-Depth Instruction. Thematic Coding.
Q: How has the Universe changed over time? $N = 3$

students were able to correctly relate a larger cosmological redshift with the galaxy being farther away from the observer (Tables 4.2 and 4.3).

In nine interviews that occurred after in-depth instruction on this topic, we asked the students for their views on how the Universe has changed over time (Figure 4.3). All nine of the students described the expansion of the Universe over time. Three of the nine (33%) referred to the usefulness of the stretchy band demonstration and 22% (2 of 9) used the phrase "Big Stretch." Both students who mentioned gravity in this context discussed how gravity keeps objects in the Solar System and/or within a galaxy in their expected orbit rather than moving according to the expansion of the Universe.

4.2. Implications

Over half of our students who addressed the movement of astronomical objects in their pre-course homework essays mentioned the expansion of the Universe. In 1989, Lightman and Miller found that only 24% of adults were aware of the notion that the Universe is expanding. It is important to keep in mind that Wallace, Prather, and Duncan (2012a) found that only 18–27% of students explicitly state that the Universe is getting bigger when describing what the "expansion of the Universe" means. A significant fraction of students instead write that the "expansion of the Universe" is a metaphor for how our knowledge of the Universe increases over time (12–30%)

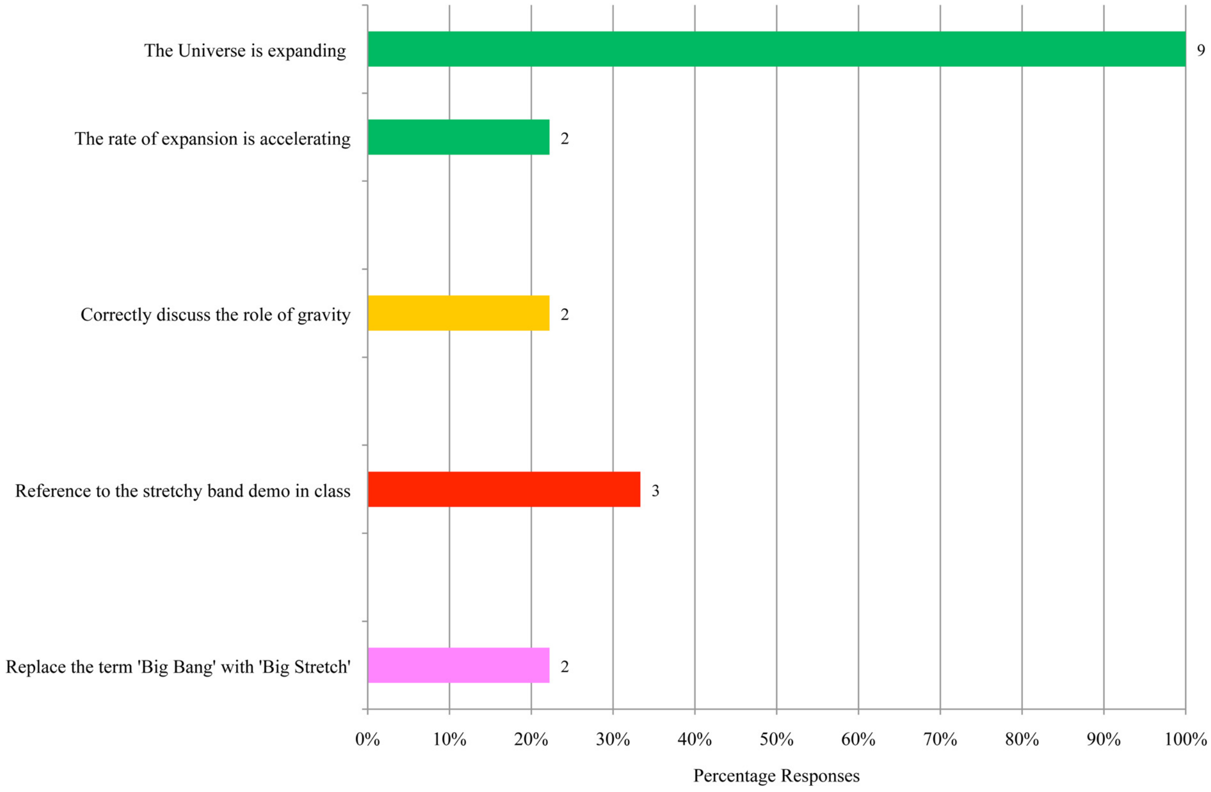


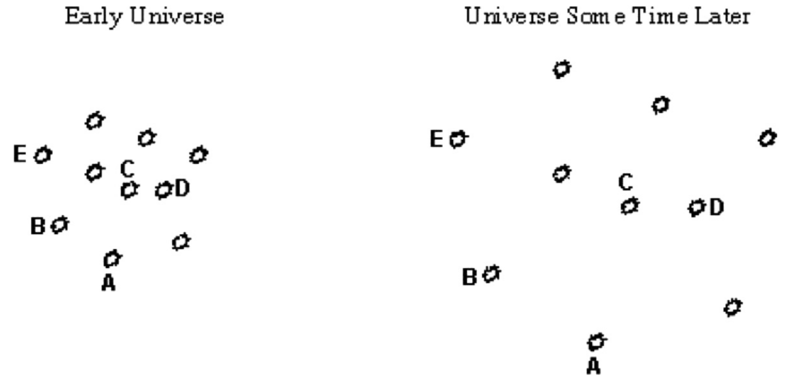
Figure 4.3. Interviews After In-Depth Instruction. Thematic Coding.
Q: How has the Universe changed over time? $N = 9$

Table 4.1. Exams. Aggregate Results

The drawing below represents the same group of galaxies at two different times during the history of the Universe. Use this drawing to answer the following question:

Which one of the following conclusions can you draw about the expansion of the universe from the drawing shown?

a. Galaxy C is the center of the universe.
b. All galaxies move the same amount during the expansion of the universe.
c. Nearby galaxies move more during the expansion of the universe.
d. **All galaxies appear to move away from each other during the expansion of the universe.**


Early Universe

Universe Some Time Later

Exam 3 ($N = 18$)

A	B	C	**D**
0%	0%	0%	**100%**

Final Exam ($N = 26$)

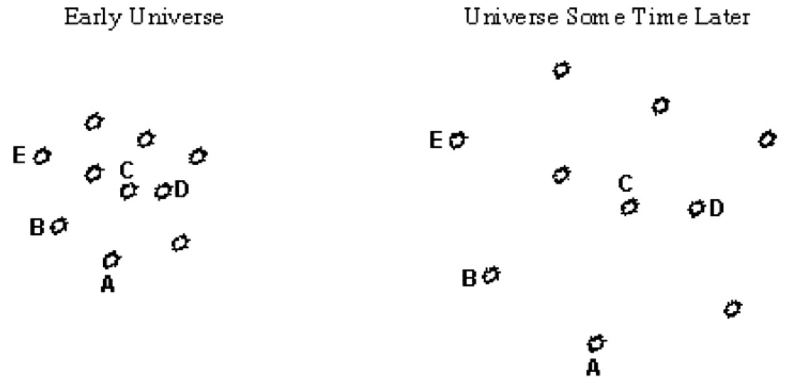
A	B	C	**D**
0%	4%	0%	**96%**

Table 4.2. Exam 3. Aggregate Result. $N = 18$

The drawing below represents the same group of galaxies at two different times during the history of the Universe. Use this drawing to answer the following question:

For an observer in galaxy B, which of the following rankings lists the speeds (from fastest to slowest) at which galaxies A, C, and D would be moving away?

a. A > C > D
b. D > A > C
c. C > D > A
d. **D > C > A**


Early Universe

Universe Some Time Later

A	B	C	**D**
11%	11%	11%	**67%**

Table 4.3. Exams. Aggregate Results
Galaxy X is measured to have a bigger cosmological redshift than Galaxy Y. Which galaxy is farther away?

Exam 3 ($N = 35$), cannot aggregate results, see Appendix for results by semester.		
C	W	NR
—	—	—
Final Exam ($N = 39$)		
C	W	NR
67%	23%	10%

or for how new objects form over time (14–16%). Our data do not allow us to determine what fraction of students holds these views.

While students may enter an astronomy course with the idea that objects in the Universe move, there is a tension between what students know about gravity causing objects to be attracted to one another on small scales and the expansion of the Universe on much larger scales. It may be telling that, of the six students who discussed the role of gravity in their pre-course homework essays, none discussed the expansion of the Universe. Our interviews that occurred after in-depth instruction provide a preliminary suggestion that this tension—the expanding Universe on large scales and the role of gravity in attracting objects together on smaller scales—may lessen through instruction. Both students who mention gravity in these interviews correctly discussed it in the sense of dominating on small scales, while expansion dominates on large scales. However, our data are insufficient to address this with statistical significance. This would be a useful point to follow up on in a future study.

Only one student in the pre-course homework essay stated the common misconception that there is no gravity in space (see Agan and Sneider 2004; Williamson and Willoughby 2012). We do not have enough data to investigate the role this misconception might have in shaping student ideas.

5. AGE OF THE UNIVERSE

An important concept in our modern understanding of cosmology is that the Universe has a finite age. One method astronomers use to estimate the age of the Universe is by measuring the rate of expansion and extrapolating back to the beginning of the universe (Komatsu *et al.* 2011). Using this method, astronomers have estimated the age of the Universe to be approximately 13.7×10^9 years. It is also possible to derive a lower limit to the age of the Universe by measuring the age of the oldest objects in the Universe (e.g., the metal-poor star, HE 1523, is 13.2×10^9 years old; Frebel *et al.* 2007).

As discussed in Section 4, our students completed a variant of the University of Washington Hubble Law laboratory (Larson *et al.*, n.d.). In this laboratory, they used real data to find the distances to galaxies using the "standard ruler approach," determine the redshifts of the galaxies from their spectral lines, and calculate the expansion rate of the Universe. They then used this expansion rate (Hubble's constant, H_0) to derive an estimate for the age of the Universe, using the mathematical representation: $t \sim 1/H_0$.

In their pre-course homework essays, 40 students discussed the age of the Universe (Figure 5.1). We asked seven of the interviewees to reflect back to what they thought about the age of the Universe prior to the start of the course (Table 5.1). Furthermore, we asked five interviewees prior to in-depth instruction to discuss their current ideas on the age of the Universe (Figure 5.2). After in-depth instruction, we asked six interviewees to discuss their ideas on the age of the Universe (Figure 5.3). Students were also asked for the age of the Universe on their exams through a MC question (Table 5.2) as well as in essay question form (Table 5.3).

None of the students discussed observational evidence for the age of the Universe in their pre-course homework essays. We asked four of the interviewees prior to in-depth instruction about how we know the age of the Universe (Figure 5.4). After in-depth instruction, we asked six interviewees to discuss their ideas on how we know the age of the Universe (Figure 5.5). Students were also asked how we know the age of the Universe

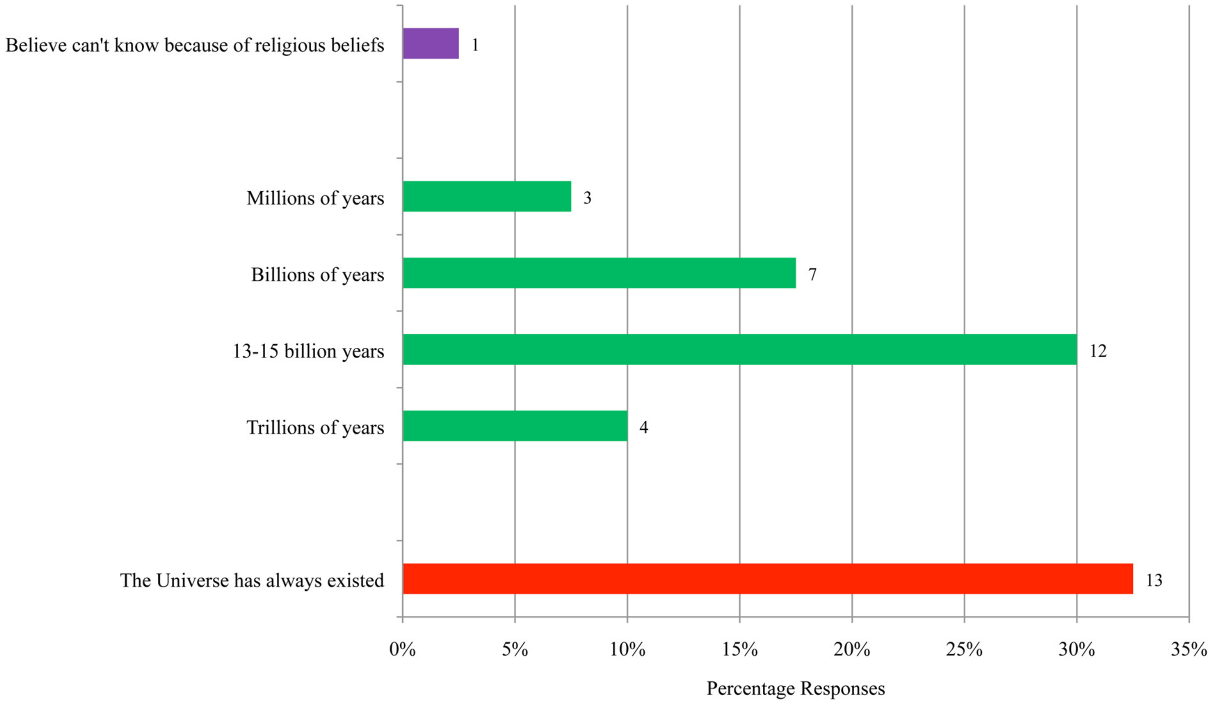


Figure 5.1. Pre-course Homework Essay. Thematic Coding.
Q: What is the age of the Universe? $N = 40$

through an exam essay question [Table 5.4, Figures 5.6(a) and 5.6(b)] and about the relationship between expansion rate and age of the Universe through T/F and FIB exam questions (Tables 5.5 and 5.6).

5.1. Finite Age of the Universe

5.1.1. Results

In the pre-course homework essays, 40 students wrote about whether the age of the Universe was finite or infinite (Figure 5.1). The majority, 65% (26 of 40) wrote that they believe the age is finite. While 30% (12 of 40) correctly provided an age between 13 and 15 billion years and 18% (7 of 40) listed the age as billions of years, 7.5% (3 of 40) contended that the age is in the millions of years and 10% (4 of 40) placed it in the trillions of years.

The pre-course homework essay responses highlight a common pre-course alternate conception that the Universe has always existed. Of the 40 students who discussed the age of the Universe in their pre-course homework essays, 13 students (33%) wrote that the Universe has always existed or been around forever (Figure 5.1).

We asked seven of the students in interviews about their pre-course ideas with regard to the age of the Universe. Six of the seven (86%) said that before the course, they thought the Universe had always existed (Table 5.1). As Interview D put it, “You know, it was just like, well, it’s here and it’s always been here.” Of the interviews that occurred prior to in-depth instruction, three of the five students (60%) asked about this topic expressed the idea

Table 5.1. Interviews (including both before and after in-depth instruction)
Q: Before taking this course, what did you think was the age of the Universe? $N = 7$

Always existed	**Finite age**
6 (86%)	1 (14%)

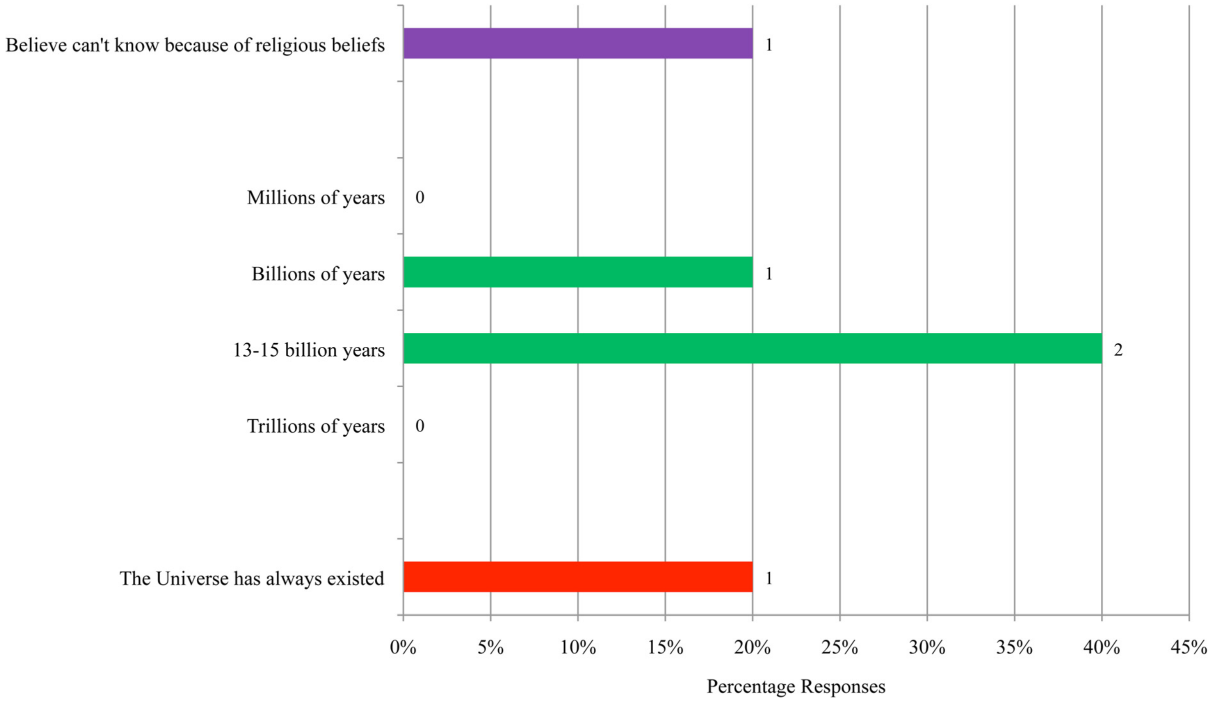


Figure 5.2. Interviews Prior to In-Depth Instruction. Thematic Coding.
Q: What is the age of the Universe? $N = 5$

that the Universe has a finite age, with two students giving it a correct age between 13 and billion years, and the third student placing it correctly in the billions of years. One student said that we cannot know the age of the Universe and one student stated that s/he thought the Universe has always existed (Figure 5.2).

Nearly all students (92%, 48 of 52) correctly identified the age as 14 billion years in the Exam 3 MC question (Table 5.2) and 84% and 81% of students correctly listed an age of 13-15 billion years on the Exam 3 and Final Exam essay question, respectively (Table 5.3). Of the 13 incorrect responses to the exam essay question, seven

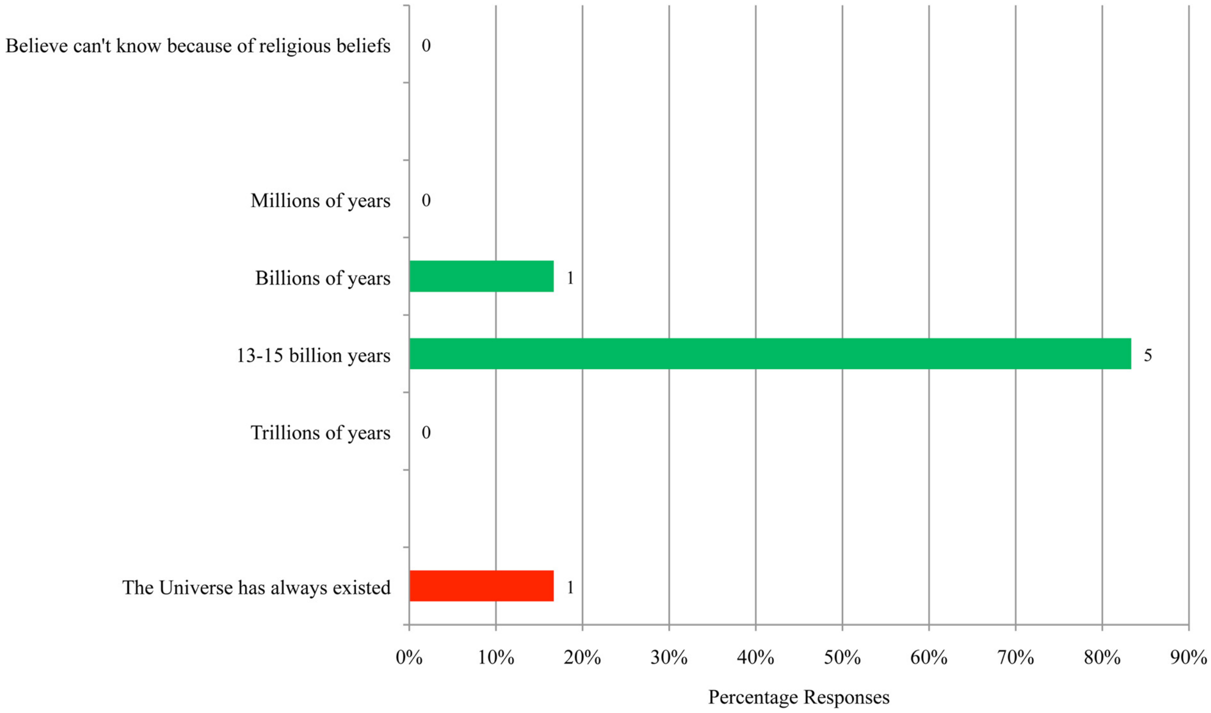


Figure 5.3. Interviews After In-Depth Instruction. Thematic Coding.
Q: What is the age of the Universe? $N = 6$

Table 5.2. Exam 3. Aggregate Result. *N* = 52

Based on observations of the universal expansion, the age of the universe is about

a. 14 million years

b. 14,000 years

c. **14 billion years**

d. 14 trillion years

A	B	**C**	D
2%	2%	**92%**	4%

Table 5.3. Exams. Essay Question. Aggregate Results

Part 1. What is the approximate age of the universe?

Correct if answer given is between 13 and 15 billion years old.

Exam 3 (*N* = 44)

C	I	P	W	T	NR	NS
84%	0%	0%	14%	0%	2%	0%

Final Exam (*N* = 48)

C	I	P	W	T	NR	NS
81%	0%	2%	15%	0%	2%	0%

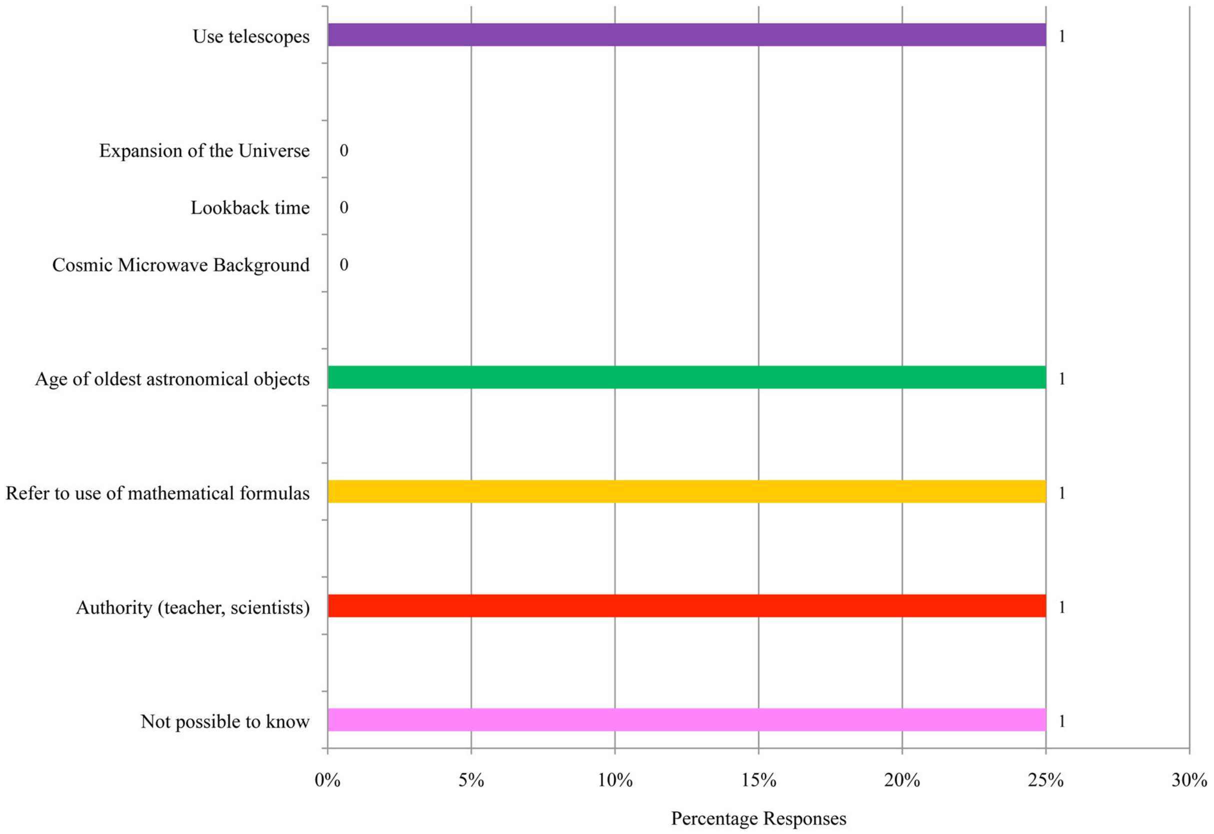


Figure 5.4. Pre-Instruction Interviews. Thematic Coding.
Q: How do we know the age of the Universe? $N = 4$

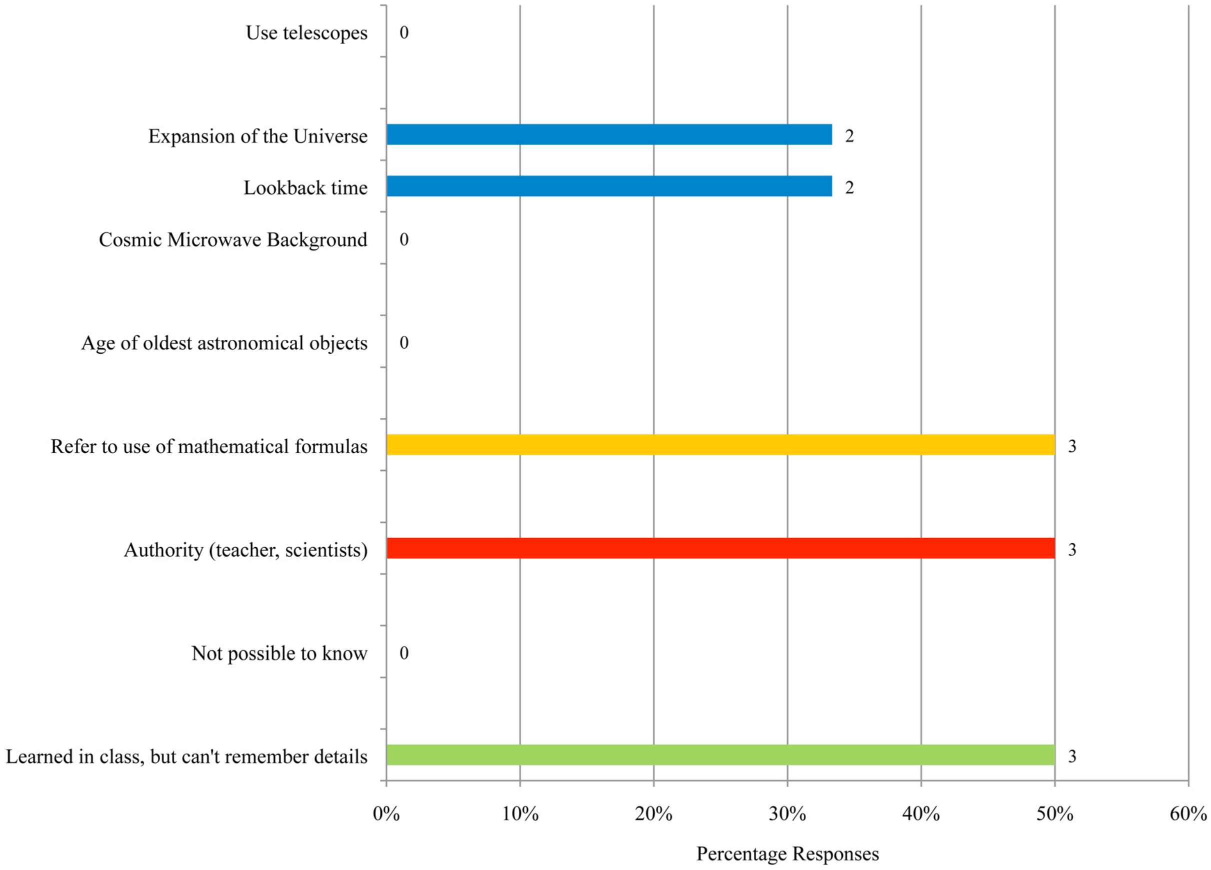


Figure 5.5. Post-Instruction Interviews. Thematic Coding.
Q: How do we know the age of the Universe? $N = 6$

listed the age in the billions of years (but not between 13 and 15), four listed the age in the millions, one wrote 400,000 years, and one wrote 4.3 billion light-years. In our interviews that occurred after in-depth instruction, 83% of students (5 of 6) stated that they had learned that the Universe has a finite age (with four listing it as between 13 and 15 billion years and one stating that it is in the billions of years; Figure 5.3).

Our exam questions do not lend themselves to probing the fraction of students who hold on to the view that the Universe has always existed after in-depth instruction. The exam questions are worded as ‘What is the approximate age of the Universe?’—within the question is the implicit hint that to get the answer correct, one should list a finite age. However, we are able to gain some insight from our interviews. Of the six students asked about the age of the Universe after in-depth instruction, one explained that s/he still believes the Universe has always and will always exist (Figure 5.3). The student expressed a view in which the Universe goes through infinite cycles of expansion and collapse (e.g., a cyclic cosmological model, as in Baum and Frampton 2007). Interview G explained, “It strikes me that the Universe ought to be timeless and that what we see is the age of this iteration of the Universe (of 13.7 billion years) and that the Universe itself is just expanding and collapsing perpetually.” It is important to note the higher level of sophistication to this view, as opposed to the simpler idea that the Universe as it is has always existed.

Table 5.4. Exams. Essay Question. Aggregate Results
Q: How do we know the age of the Universe?

Exam 3 ($N = 44$)

C	I	P	W	T	NS	NR
0%	48%	9%	5%	4%	0%	34%

Final Exam ($N = 48$)

C	I	P	W	T	NS	NR
0%	56%	12%	8%	0%	0%	23%

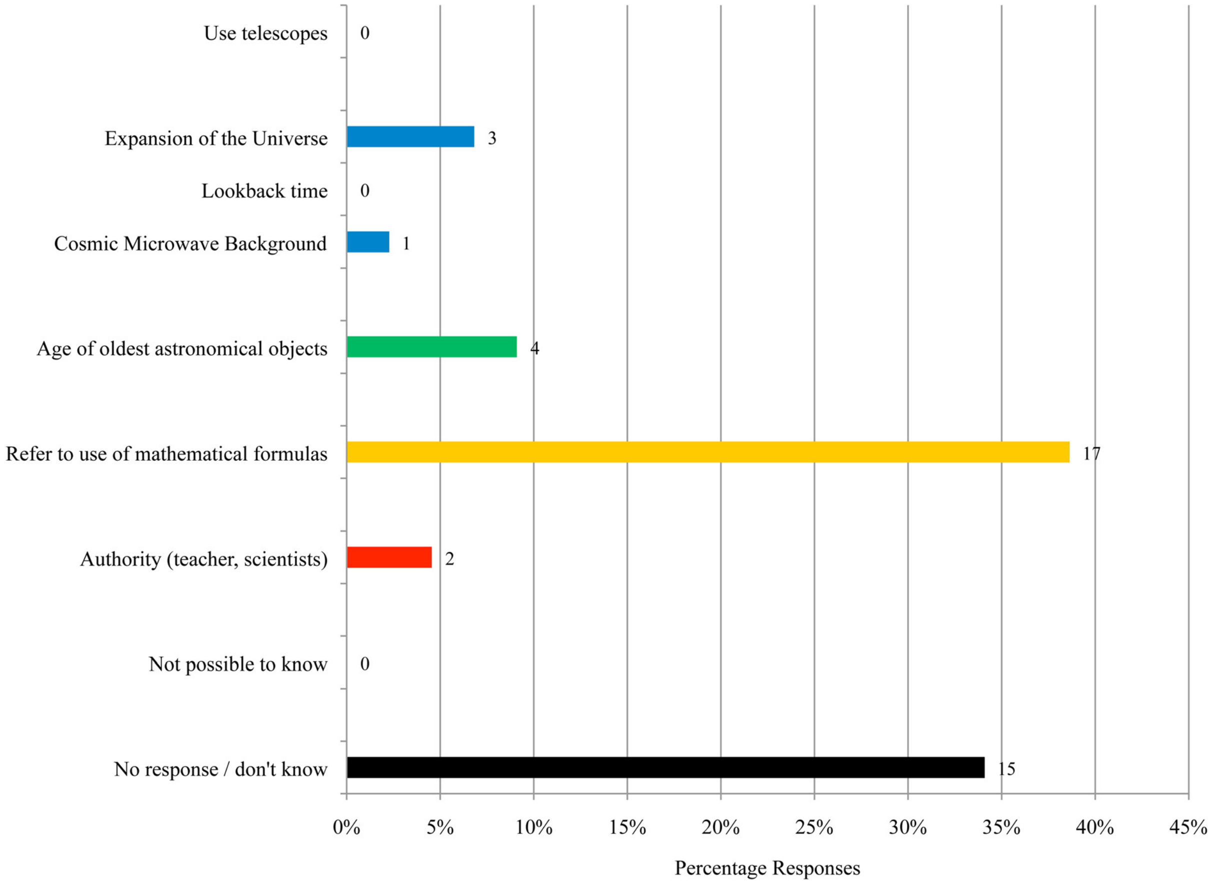


Figure 5.6a. Exam 3. Essay Question. Thematic Coding.
How do we know the age of the Universe? $N = 44$

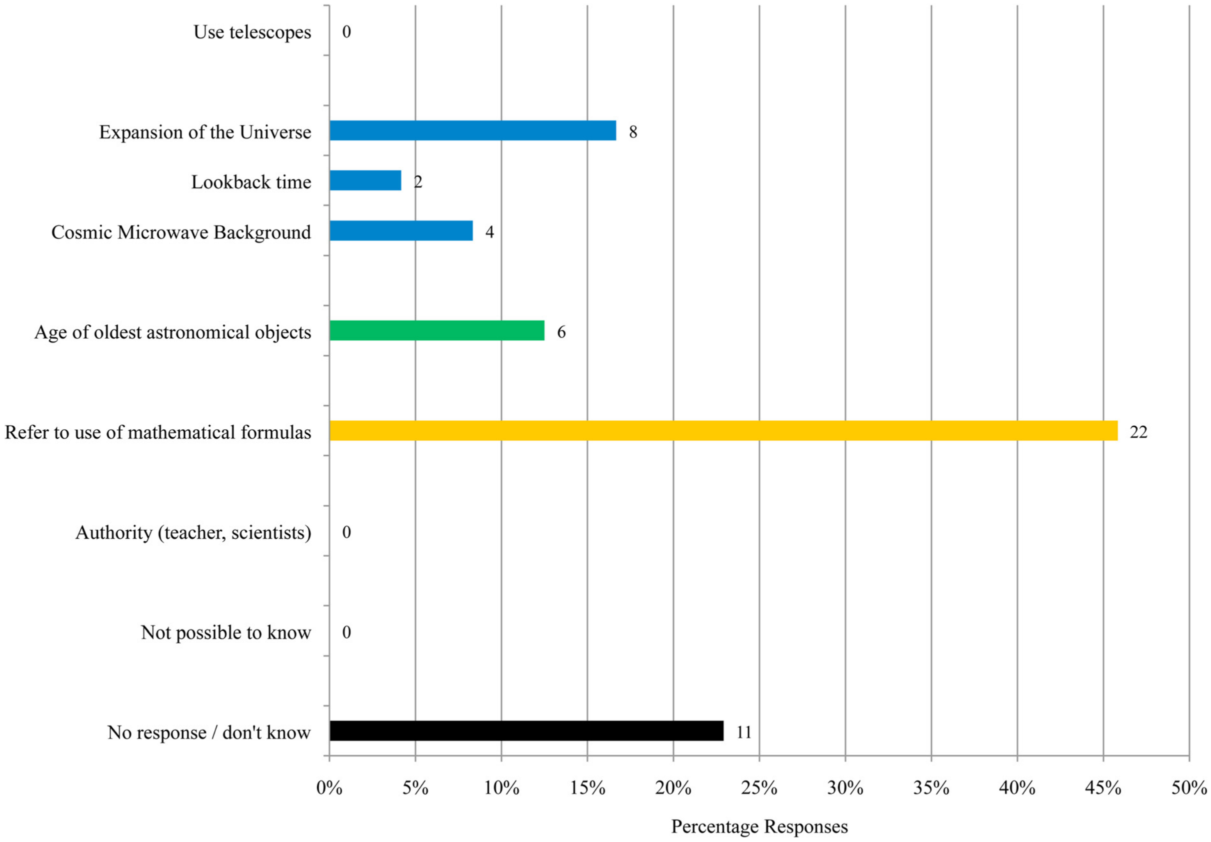


Figure 5.6b. Final Exam. Essay Question. Thematic Coding.
How do we know the age of the Universe? $N = 48$

Table 5.5. Exam 3. T/F. Aggregate Result
The faster the rate of expansion, the older the age of the universe. T / **F**

T	**F**	NR
25%	**62%**	3%

5.1.2. *Implications*

The majority of students enter an introductory astronomy course with the idea that the Universe has a finite age (67%, our pre-course homework essays; 58%, Bailey *et al*. 2012). However, a notable fraction enters with the idea that the Universe has always existed (30% in our pre-course homework essays; six of seven of our interviewees on their pre-course ideas; 26%, Bailey *et al*. 2012).

Following in-depth instruction, we found that one of six interviewees persisted in believing the Universe has always existed. The student expressed a view akin to a cyclic cosmological model, in which the Universe goes through infinite cycles of expansion and collapse, and we are at ∼14 billion years into our current cycle. Although not enough detail was provided in the pre-course homework essay or in the Bailey *et al*. 2012 surveys to be certain, it is unlikely that this view is held by many students prior to instruction.

The persistence in believing the Universe has always existed may be related to another common alternate conception observed by Prather, Slater, and Offerdahl (2002)—70% of students believe the “Big Bang” organizes pre-existing matter (also see Wallace, Prather, and Duncan 2012a). Prather, Slater, and Offerdahl hypothesized that this is a result of students operating from the p-prim “you can’t make something from nothing,” and applying this intuitive knowledge to the Big Bang Theory. In their study, they explained that students often asked, “What is the Universe expanding into?” and suggested that students have a mental picture of the “Big Bang” as a primordial grenade exploding into a pre-existing room (also see Pimbblet 2002 for his study of what he labels the “ex-nihilo obstacle”).

5.2. Deriving the Age of the Universe

5.2.1. *Results*

In our pre-course homework essays, none of the 43 students who discussed the age of the Universe described how we know the age of the Universe. However, because we did not ask the question explicitly in the assignment, we are unable to determine if this silence is because the students don’t know or believe we cannot know, or if they simply did not write down their ideas on this point.

The interviews do provide us some insight. In four of the pre-instruction interviews (i.e., of the students who had not yet done the Hubble Law laboratory), we asked about how scientists derive an estimate for the age of the Universe. The four responses were evenly divided between (1) we can’t know, (2) a scientist or person of authority tells us, (3) we use mathematical formulas, and (4) we use the ages of the oldest stars and galaxies (Figure 5.4). The student who responded that we cannot know (Interview C) explained, “We don’t have the

Table 5.6. Exams. FIB. Aggregate Results
The slower the rate of expansion, the **older** the age of the universe.

Exam 3 ($N = 30$)		
C	W	NR
63%	33%	3%
Final Exam ($N = 23$)		
C	W	NR
61%	39%	0%

technology to go like far, far out in space. It's not like testing the age of trees. You can't just be like 'oh look at those six rings, it's forty years.'"

We asked six students about how we know the age of the Universe in interviews after they had completed the Hubble Law laboratory. Three of the students discussed the formulas and mathematical reasoning used to derive the age of the Universe (and two of these students explicitly tied this to the rate of expansion of the Universe), while three of the students simply noted that they learned how to derive the age of the Universe in class, but were unable to provide explicit details on the process (Figure 5.5).

Exam results similarly suggest that the majority of students struggle in understanding the actual measurements they carried out to determine the age. For example, no student was fully correct in his/her response to the exam essay question, "How do we know the age of the Universe? Describe the measurements and calculations you would use to determine it" (Table 5.4). A notable fraction, 34% of students (15 of 44) on Exam 3 and 23% of students (11 of 48) on the Final Exam, left the question blank. Specifically, students do not have a clear conceptual understanding of why the ratio between distance and recessional velocity (that they measured in the lab) is related to expansion rate. Nor do they have a clear understanding of why the mathematical formula, $t = 1/H_0$, is a representation of the concept that the age of the Universe depends on the expansion rate. A significant fraction of students received an 'Incomplete' on this essay question: 48% (21 of 44) on Exam 3 and 56% (27 of 48) on the Final Exam. Most were incomplete because they listed the formula ($t = 1/H_0$) without providing an explanation or they were missing at least one of the following components: (1) both the distance and recessional velocity are used to derive the expansion rate (the Hubble constant) and (2) the inverse of the Hubble constant provides an estimate for the age. Of the 9% on Exam 3 and 12% on the Final Exam who received a "Partial" and the 5% on Exam 3 and 8% on the Final Exam who were "Wrong," the majority incorrectly labeled the axes (such as with mass, chemical composition, or time) for the plot of the Hubble Law.

In our thematic coding of the exam responses [Figures 5.6(a) and 5.6(b)], the most common correct responses involved presenting the mathematical reasoning (42% or 17 of 44 students on Exam 3 and 46% or 22 of 48 students on the Final Exam), invoking the Hubble constant (27% or 12 of 44 students on Exam 3 and 35% or 17 of 48 students on the Final Exam), describing the implications of the expansion of the Universe (7% or 3 of 44 students on Exam 3 and 17% or 8 of 48 students on the Final Exam), and using the age of the oldest astronomical objects (9% or 4 of 44 students on Exam 3 and 13% or 6 of 48 students on the Final Exam).

Despite the difficulty in understanding the details of the calculations, the exam results show that students have a reasonably good conceptual understanding of the relation between the rate of expansion and the age of the Universe, with a faster rate of expansion leading to a younger Universe. Specifically, over 60% of students correctly responded to T/F and FIB exam questions testing this concept (Tables 5.5 and 5.6).

5.2.2. Implications

Students enter their astronomy courses with little to no knowledge of how astronomers derive the age of the Universe. In their pre-course surveys, Bailey *et al.* (2012) found that student ideas on how we determine the age of the Universe largely fall under the categories of "I don't know"/no response (28%), "we can't know" (18%), and "scientists tell us" (14%). For responses that included mention of a scientific process or phenomenon, the majority were simplistic, inaccurate, or based on too small a timescale, such as carbon dating of fossils. Our pre-instruction interviews tell a similar story.

Exam results show that students struggle with understanding the actual measurements used to derive the age of the Universe, despite having done an extensive lab in which they carry out the process for themselves. No student is fully correct and over a quarter of the students leave this question blank on the exams. This difficulty in describing the process of deriving the age is not surprising given previous studies of students' difficulties with graph interpretation and kinematic quantities (McDermott, Rosenquist, and van Zee 1987; Trowbridge and McDermott 1980).

On the other hand, we do see progress in student conceptual understanding. Over 60% of our students respond correctly to the exam questions relating the rate of expansion and the age of the Universe. Furthermore, all of our postinstruction interviewees indicated that they knew of specific evidence supporting our current best estimate for the age of the Universe (in spite of not knowing the details of the measurements).

6. HISTORY OF THE UNIVERSE

An overarching theme of the CSU astronomy course is that the Universe evolves over time. In terms of the Big Bang Theory, we focus on three major concepts regarding this evolution: (1) the Universe expands, (2) the Universe becomes less dense, and (3) the Universe cools. We discussed student ideas on these topics in detail in Section 3. A related learning objective was for the students to be able to describe and have a sense of the timing of major cosmological events in the history of the Universe, including: the formation of light elements a few minutes after the beginning of the Universe, the release of the CMB photons at ∼400,000 years; the formation of the first stars and galaxies at a few hundred million years; and the formation of our Solar System at ∼9.5 billion years.

In addition to a mini-lecture on this topic at the start of the semester, we support student learning that the Universe changes over time by discussing cosmologically important events throughout the history of the Universe. We do this through a mini-lecture later and the CSU-developed activity "The Cosmic Timeline." In this activity, the students construct a scale drawing of cosmic time covering the entire history of the Universe, with 10 cm equal to 1 billion years.

In the pre-course homework essays, 60% of the students (33 of 55) discussed at least one aspect of the timeline for cosmological events (Figure 6.1). Five of the fifteen interviewees were asked about the timing of major cosmological events; two prior to in-depth instruction and three after in-depth instruction on this topic (Figure 6.2). The exam essay question, "Briefly describe 4 cosmologically important events in the history of the Universe," allows us to track student ideas later in the course as well [Table 6.1 and Figures 6.3(a) and 6.3(b)].

6.1. Results

Of the 33 students who discuss the timing of cosmological events in their pre-course homework essays, 10 (30%) wrote that the stars, galaxies, and/or planets formed at the same time or very soon after the creation of the Universe (Figure 6.1). For example, one student wrote in his/her pre-course homework essay, "I believe the Universe, earth, planets, the moon, and the sun were all created at the same time." Interview responses, both prior to and after in-depth instruction, expressed similar ideas. For example, Interview A said: "I think the planets are a part of that ['Big Bang'] explosion, I'm not really sure, but I think they are". Interview J explained during a postinstruction interview, "I thought [pre-instruction] that there was one big massive structure that exploded and one planet went that way and that planet went another way and the sun shot to the middle."

Four students (12%) wrote in their pre-course homework essays that the Universe, stars, galaxies, and planets have all existed forever (related to the common alternate conception discussed in Section 5 that the age of the Universe is not finite). Finally, a notable fraction (58%; 19 of 33 students) in their pre-course homework essays did correctly describe in general terms that the stars, galaxies, and planets formed a significant time after the Universe was created (Figure 6.1).

In response to the exam essay question, "Briefly describe 4 cosmologically important events in the history of the Universe," common correct responses included the following [note: the percentages refer to Exam 3 and Final Exam results, respectively, see Figures 6.3(a) and 6.3(b)]:

- phases in the early Universe (e.g., the Planck era: 35%–39%, particle soup: 21%–22%, the annihilation of anti-matter with matter: 16%–17%),
- Big Bang nucleosynthesis during the first few minutes (49%–67%),
- the emission of the CMB at 400,000 years (37%–39%),
- the birth of the first stars and galaxies at several hundred million years (58%–56%),
- and the formation of the Solar System at ∼9.5 billion years (26%–61%).

However, only one student (of 43) on Exam 3 and three students (of 18) on the Final Exam were able to provide both the correct timing and description for four cosmological events (Table 6.1). Of the "Partial" responses, the

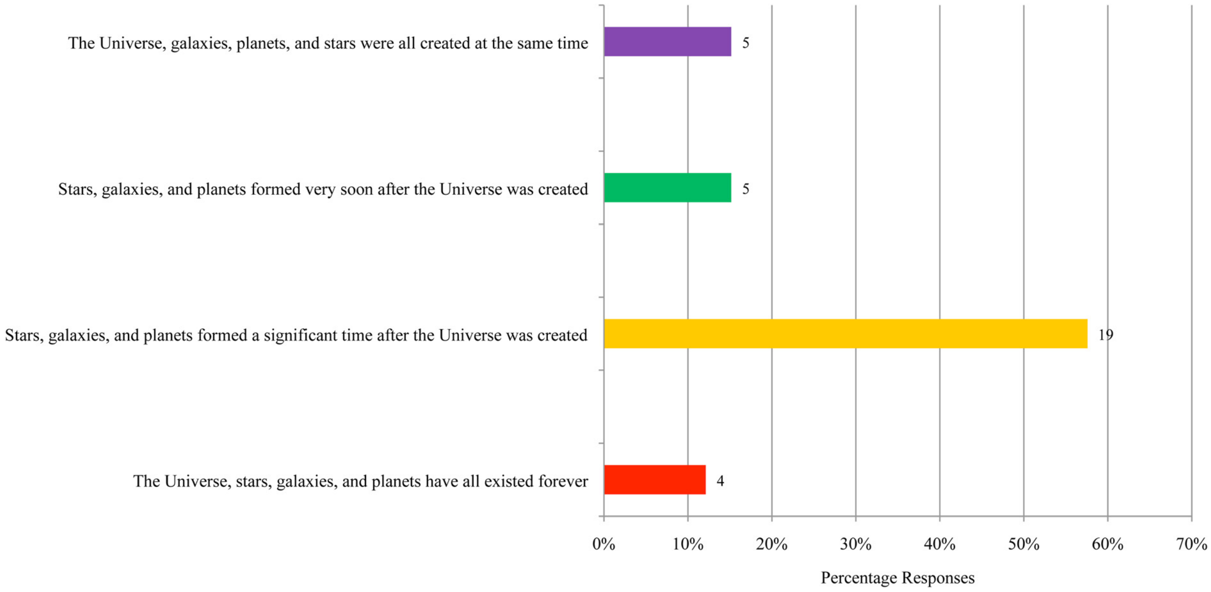


Figure 6.1. Pre-course Homework Essay. Thematic Coding.
Q: Timeline for Cosmological Events, $N = 33$

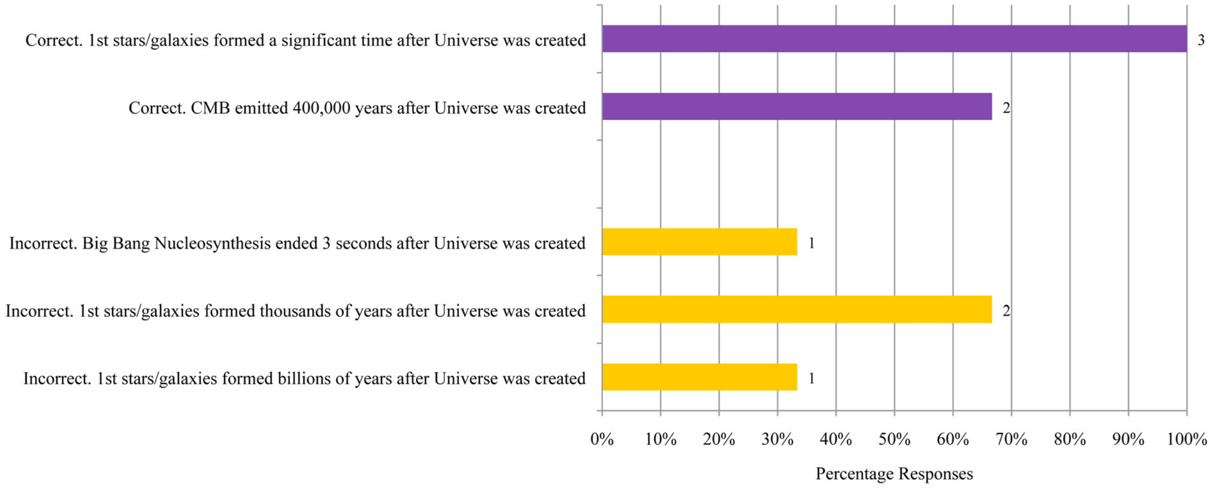


Figure 6.2. Post-Instruction Interviews. Thematic Coding.
Q: Timeline for Cosmological Events, $N = 3$

Table 6.1. Exams. Essay Question. Aggregate Results
Q: Briefly describe 4 cosmologically important events in the history of the Universe. For each event, give the approximate age of the Universe and what conditions were like then.

Exam 3 ($N = 43$)

C	I	P	W	NR
2%	39%	51%	0%	7%

Final Exam ($N = 18$)

C	I	P	W	NR
17%	33%	44%	0%	6%

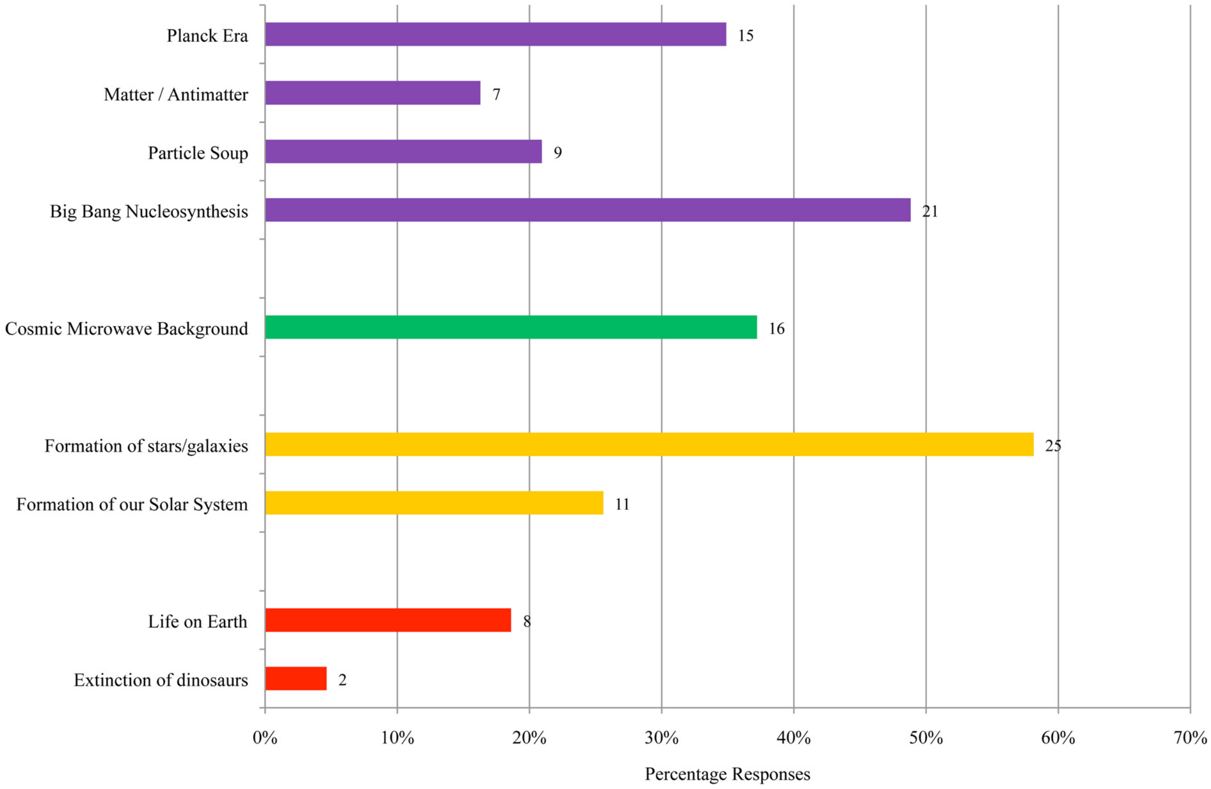


Figure 6.3a. Exam 3. Essay Question. Thematic Coding.
Q: Briefly describe 4 cosmologically important events in the history of the Universe. For each event, give the approximate age of the Universe and what conditions were like then, $N = 43$

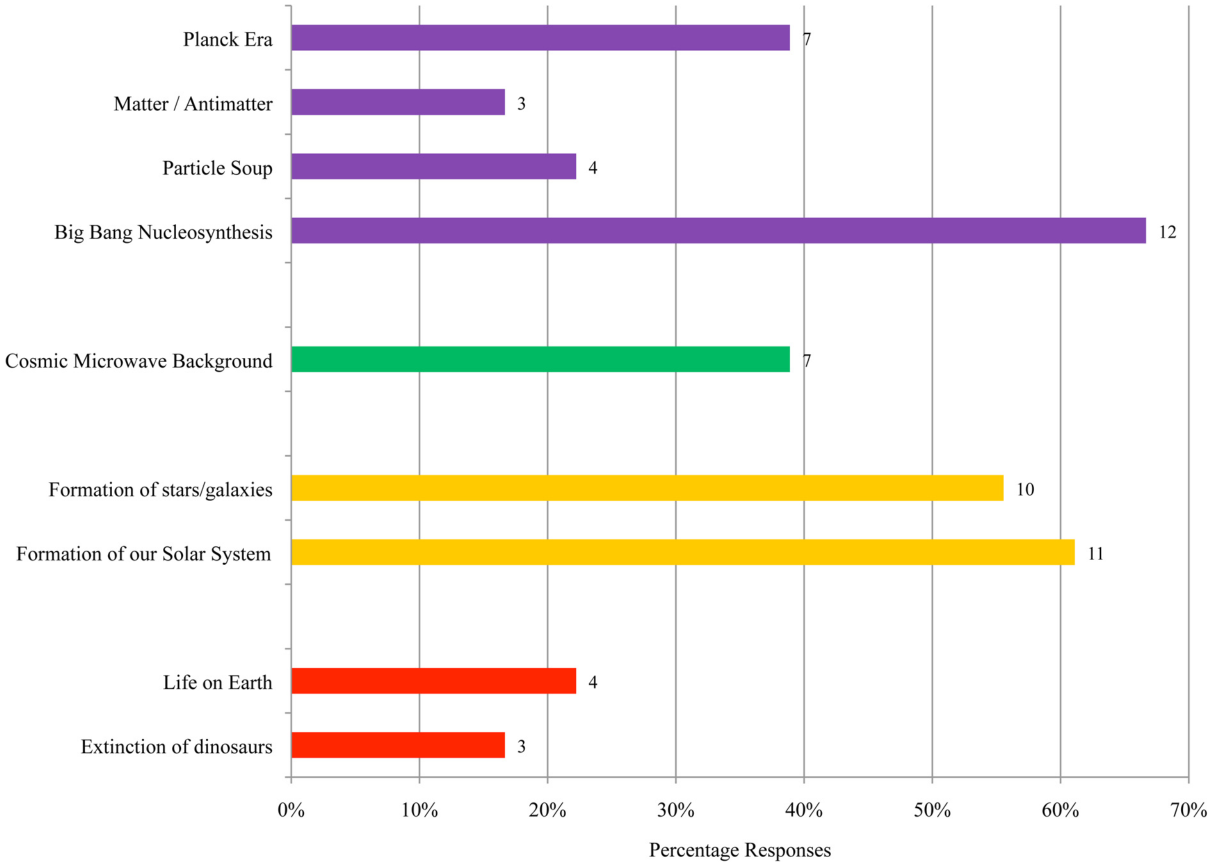


Figure 6.3b. Final Exam. Essay Question. Thematic Coding.
Q: Briefly describe 4 cosmologically important events in the history of the Universe. For each event, give the approximate age of the Universe and what conditions were like then, $N = 18$

majority had the wrong timescale listed for a given event (as opposed to the wrong description). A common incorrect timescale response (for example, 8 of 19 on Exam 3) was to list that the first stars and galaxies formed within the first few minutes of the Universe's existence. Also, 2 students on Exam 3 and 3 students on the Final Exam mentioned the extinction of dinosaurs and 8 students on Exam 3 and 4 students on the Final Exam mentioned life on Earth as cosmologically important events.

All three of the post in-depth instruction interviewees correctly stated that it took significant time for the first stars and galaxies to form. Two of the three also gave the correct timing for the CMB emission at 400,000 years. Yet none of the three had the correct order of magnitude for when the first stars and galaxies formed; two said that they formed thousands of years after the Universe was created and one said they formed billions of years after the Universe was created (see Figure 6.2).

6.2. Implications

In Section 3.1, we discussed the common alternate conception that the Big Bang Theory directly describes the creation of stars, planets, and/or our Solar System. Here, we examine more specifically the alternate conception that the timing of cosmologically important events was very fast or even immediate.

In the pre-course homework essays, over half the students correctly wrote that the stars, galaxies, and planets formed a significant time after the beginning of the Universe. However, one-third wrote that the stars, galaxies, and/or planets came into existence at the same time or soon after the formation of our Universe. Even after in-depth instruction, only a few students were able to provide both the correct timing and description for four cosmological events in response to the exam essay question on this topic. The majority of the incorrect responses were a result of students stating that the first stars and galaxies formed within the first few minutes.

7. SUMMARY

In Paper I of this series, we investigated student ideas on astronomical distances and structure (Coble *et al.* 2013). In Paper II of this series, we examined student ideas on the composition of the Universe (Coble *et al.*, in preparation). Here, in Paper III of the series, we have investigated student ideas about the Big Bang Theory, the expansion of the Universe, the age of the Universe, and the timing of cosmological events. We used course artifacts and in-depth interviews to identify student ideas.

As has been the case in many areas of science, we find that students entering our ASTRO 101 courses bring with them a wide variety of ideas, both aligned with and different from scientific knowledge. Specific to cosmology, we explore a number of common student ideas; our findings include the following:

- Student understanding of the conditions in the early Universe is weak at the start of the course. Pre-instruction, few students describe the early Universe as hot and dense. By the end of the semester, student understanding of these characteristics of the early Universe was fairly robust. However, exam responses suggest that a difficult aspect to assimilate is that the Universe's overall temperature decreases with time. Students may be confusing the small-scale heating/cooling by local events like supernova explosions and the large-scale, long-term cooling of the Universe as it expands.
- A large number of students enter the course with the idea that the 'Big Bang' refers to an explosion, and that the creation of our Universe began with an explosion. In exams, students responded correctly to a T/F question on this topic, but in-depth interviews suggest that this mental model is difficult to replace.
- Prior to instruction, at least one-third of students think that the stars, galaxies, and/or planets form at the same time or soon after the creation of the Universe. This may be related to our finding in Paper I of this series that students conflate the terms solar system, galaxy, and Universe, and/or this may be a result of a lack of understanding of the timeline of major cosmological events (i.e., our Solar System formed 9.5 billion years after the formation of our Universe). A subset of students hold on to this alternate conception through to the end of the semester, indicating that this can be a difficult concept to assimilate.
- At least one-third of students enter the course with the idea that the Universe has always existed. By the end of the course, the majority of students are familiar with the scientifically derived age of the Universe.

However, student understanding of the details of the calculations for deriving the age of the Universe is impaired by weak math and graph-reading skills.
- The majority of students do not know of any evidence in support of the Big Bang Theory prior to instruction. Student knowledge of evidence improved over the course of the semester, yet approximately one-quarter left exam questions on this topic blank. Also, while a common response for evidence supporting the Big Bang Theory was the CMB, most students were unable to provide an explanation for why.
- Once students learn about dark matter and dark energy, they may be prone to incorrectly associating these complex concepts with evidence for the Big Bang Theory. For example, while no students cited dark matter or dark energy as evidence for the Big Bang Theory pre-instruction, a notable fraction incorrectly referred to dark energy and/or dark matter as evidence for the Big Bang Theory in exam responses.

With awareness of these alternate conceptions, we can better help students move toward improved understanding of both the processes and outcomes of cosmology, and of science and mathematics more generally. This research is part of a larger effort to develop curricular materials for introductory astronomy courses in which students participate in the process of doing science while learning concepts in modern cosmology. Specifically, the results of this research are being used to inform the design of a series of web-based cosmology learning modules for general education undergraduate students (Coble *et al*. 2012; Coble *et al*., in preparation).

Acknowledgments

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NOTES

NOTE 1: http://www.nextgenscience.org/next-generation-science-standards/

NOTE 2: The Big Bang Theory refers to the explanation for the evolution of the Universe over time. Astronomers sometimes colloquially refer to the early moments of the Universe's existence as the "Big Bang." As we will see, student use of the terms "Big Bang" and Big Bang Theory sometimes differ from their scientific use.

NOTE 3: Although newer editions are now available, the first edition was used at the time of these courses.

NOTE 4: masteringastronomy.com

NOTE 5: gtn.sonoma.edu

NOTE 6: The parametric equivalent to the KW test is the one-way analysis of variance (ANOVA). The KW test is an extension of the Mann-Whitney U test (which analyzes sample pairs for differences) to three or more groups.

NOTE 7: Big Bang nucleosynthesis explains why there is an abundance of light elements in comparison to heavier elements. As such, it provides cosmologists with a very good method of testing the quantitative predictions of the Big Bang Theory.

NOTE 8: The original class work and exam questions used the word 'model' and the term 'Big Bang Model' to avoid confusion with the colloquial use of the word 'theory'. In the text of this article, we have chosen to use the word 'theory' and the phrase "Big Bang Theory," but we have left the exam questions in their original wording.

NOTE 9: A stretchy athletic band with galaxies stapled along its length to demonstrate the expansion of space between galaxies and a video of the history of the Universe moving backwards in time, such as the American Museum of Natural History's 'The Known Universe', posted at http://apod.nasa.gov/apod/ap100120.html.

NOTE 10: http://www.cfa.harvard.edu/seuforum/download/CQEdGuide.pdf.

Appendix

The tables below correspond with the summary tables in the main body of the paper (e.g., Table 3.1 corresponds to Tables A3.1a and A3.1b, Table 3.2 corresponds to Table A3.2, etc.). These appendix tables include the original question, the answer, the detailed *N*'s and percentages for different semesters, and the H-statistics and p-values from KW tests (or KS-statistics and p-values from KS tests, as appropriate).

A3. BIG BANG THEORY

Table A3.1a. Exam 3. Essay Question

Q: Describe the Big Bang Model.

A: The Big Bang Model explains how the Universe changes over time. The Universe was hotter and denser in the past, and has been expanding and cooling over time.

	Fall 2008 $N = 9$	**Spring 2009** $N = 9$	**Spring 2010** $N = 11$	**Fall 2010** N/A	**Spring 2011** $N = 13$	**Total** $H = 1.85$ $p = 0.61$ $N = 42$
C	**0 (0%)**	**0 (0%)**	**2 (18%)**	**—**	**5 (38%)**	**7 (17%)**
I	5 (56%)	6 (67%)	6 (55%)	—	3 (23%)	20 (48%)
P	2 (22%)	1 (11%)	0 (0%)	—	4 (31%)	7 (17%)
W	2 (22%)	2 (22%)	2 (18%)	—	0 (0%)	6 (14%)
T	0 (0%)	0 (0%)	0 (0%)	—	0 (0%)	0 (0%)
NS	0 (0%)	0 (0%)	0 (0%)	—	0 (0%)	0 (0%)
NR	0 (0%)	0 (0%)	1 (9%)	—	1 (8%)	2 (5%)

Table A3.1b. Final Exam. Essay Question

Q: Describe the Big Bang Model.

A: The Big Bang Model explains how the Universe changes over time. The Universe was hotter and denser in the past, and has been expanding and cooling over time.

	Fall 2008 $N = 10$	**Spring 2009 $N = 9$**	**Spring 2010 N/A**	**Fall 2010 $N = 13$**	**Spring 2011 $N = 13$**	**Total $H = 0.75$ $p = 0.86$ $N = 45$**
C	**1 (10%)**	**0 (0%)**	—	**0 (0%)**	**4 (32%)**	**5 (11%)**
I	8 (80%)	8 (89%)	—	10 (77%)	5 (38%)	31 (69%)
P	0 (0%)	0 (0%)	—	2 (15%)	2 (15%)	4 (9%)
W	1 (10%)	1 (11%)	—	1 (8%)	2 (15%)	5 (11%)
T	0 (0%)	0 (0%)	—	0 (0%)	0 (0%)	0 (0%)
NS	0 (0%)	0 (0%)	—	0 (0%)	0 (0%)	0 (0%)
NR	0 (0%)	0 (0%)	—	0 (0%)	0 (0%)	0 (0%)

Table A3.2. Exam 3. T/F

Q: The Universe began with a giant explosion, like a bomb. T/**F**.

	Fall 2008 N/A	**Spring 2009 $N = 9$**	**Spring 2010 $N = 12$**	**Fall 2010 $N = 13$**	**Spring 2011 $N = 13$**	**TOTAL $H = 0.73$ $p = 0.87$ $N = 47$**
T	—	0 (0%)	2 (17%)	0 (0%)	0 (0%)	2 (4%)
F	—	**9 (100%)**	**10 (83%)**	**13 (100%)**	**13 (100%)**	**45 (96%)**

Table A3.3. Final Exam. MC

Q: According to modern ideas and observations, what can be said about the location of the center of our expanding universe?

a. The earth is at the center
b. The Sun is at the center
c. The Milky Way Galaxy is at the center
d. **The Universe does not have a center**

	Fall 2008 $N = 10$	**Spring 2009 $N = 9$**	**Spring 2010 $N = 12$**	**Fall 2010 $N = 13$**	**Spring 2011 N/A**	**Total $H = 0.26$ $p = 0.97$ $N = 44$**
A	1 (10%)	0 (0%)	0 (0%)	0 (0%)	—	1 (2%)
B	0 (0%)	0 (0%)	0 (0%)	0 (0%)	—	0 (0%)
C	0 (0%)	0 (0%)	0 (0%)	1 (8%)	—	1 (2%)
D	**9 (90%)**	**9 (100%)**	**12 (100%)**	**12 (92%)**	—	**42 (96%)**

Table A3.4a. Exam 3. Essay Question

Q: Describe two pieces of observational evidence for the Big Bang Model.

(Must have 2 out of the following 3 to be ‘Correct’)

1) We observe that the Universe is expanding (Variation: By simulating the evolution of our Universe in reverse, we can recreate the conditions for the Big Bang Model’s description of the early Universe.)
2) The composition of atoms is consistent with the Big Bang Model. The observed amounts of light chemical elements, such as Deuterium, Helium, and Lithium could not have formed in stars. These elements were created in the first few minutes, when the universe was hot enough for nuclear fusion to occur.
3) The Cosmic Microwave Background (CMB), a nearly uniform glow of microwave radiation in all directions, with a temperature of 2.73 K. (*Note*: if they only listed the term “CMB,” but included no description, we placed the response in the appropriate “-L,” for “list,” category.)

	Fall 2008 $N = 9$	**Spring 2009 $N = 9$**	**Spring 2010 $N = 12$**	**Fall 2010 N/A**	**Spring 2011 N/A**	**Total $H = 0.06$ $p = 0.97$ $N = 30$**
C	**1 (11%)**	**0 (0%)**	**0 (0%)**	**—**	**—**	**1 (3%)**
I	0 (0%)	2 (22%)	2 (17%)	—	—	4 (13%)
P	2 (22%)	1 (11%)	2 (17%)	—	—	5 (17%)
W	1 (11%)	2 (22%)	3 (25%)	—	—	6 (20%)
T	0 (0%)	0 (0%)	0 (0%)	—	—	0 (0%)
C-L	4 (44%)	0 (0%)	2 (17%)	—	—	6 (20%)
I-L	0 (0%)	2 (22%)	0 (0%)	—	—	2 (7%)
P-L	0 (0%)	0 (0%)	1 (8%)	—	—	1 (3%)
NS	0 (0%)	0 (0%)	0 (0%)	—	—	0 (0%)
NR	1 (11%)	2 (22%)	2 (17%)	—	—	5 (17%)

Table A3.4b. Final Exam. Essay Question

Q: Describe two pieces of observational evidence for the Big Bang Model.

Must have 2 out of the following 3 to be correct:

1) We observe that the Universe is expanding. (Variation: By simulating the evolution of our Universe in reverse, we can recreate the conditions for the Big Bang Model’s description of the early Universe.)
2) The composition of atoms is consistent with the Big Bang Model. The observed amounts of light chemical elements, such as Deuterium, Helium, and Lithium could not have formed in stars. These elements were created in the first few minutes, when the universe was hot enough for nuclear fusion to occur.
3) The Cosmic Microwave Background (CMB), a nearly uniform glow of microwave radiation in all directions, with a temperature of 2.73 K. (Note: if they only listed the term CMB, but included no description, we mark as ‘L’, for ‘list’.)

	Fall 2008 $N = 10$	**Spring 2009 $N = 9$**	**Fall 2010 N/A**	**Spring 2010 N/A**	**Spring 2011 N/A**	**Total $KS = 0.19$ $p = 0.95$ $N = 19$**
C	**1 (10%)**	**0 (0%)**	—	—	—	**1 (5%)**
I	2 (20%)	1 (11%)	—	—	—	3 (16%)
P	2 (20%)	0 (0%)	—	—	—	2 (10%)
W	0 (0%)	1 (11%)	—	—	—	1 (5%)
T	0 (0%)	0 (0%)	—	—	—	0 (0%)
C-L	1 (10%)	2 (22%)	—	—	—	3 (16%)
I-L	1 (10%)	3 (33%)	—	—	—	4 (21%)
P-L	1 (10%)	0 (0%)	—	—	—	1 (5%)
NS	0 (0%)	0 (0%)	—	—	—	0 (0%)
NR	2 (20%)	2 (22%)	—	—	—	4 (21%)

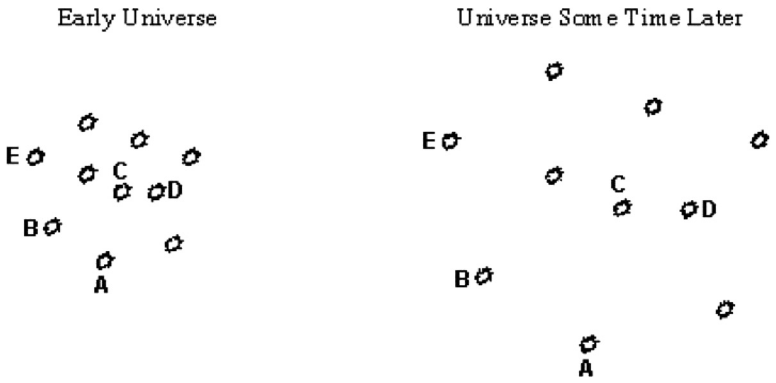
A4. EXPANSION

Table A4.1a. Exam3. MC

The drawing below represents the same group of galaxies at two different times during the history of the Universe. Use this drawing to answer the following question:

Which one of the following conclusions can you draw about the expansion of the universe from the drawing shown?

a. Galaxy C is the center of the universe.
b. All galaxies move the same amount during the expansion of the universe.
c. Nearby galaxies move more during the expansion of the universe.
d. **All galaxies appear to move away from each other during the expansion of the universe.**



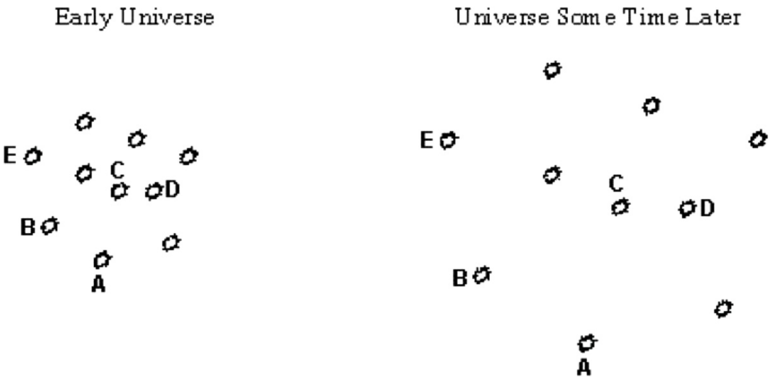
	Fall 2008 *N* = 9	Spring 2009 *N* = 9	Spring 2010 N/A	Fall 2010 N/A	Spring 2011 N/A	Total *KS* = 0.00 *p* = 1.00 *N* = 18
A	0 (0%)	0 (0%)	—	—	—	0 (0%)
B	0 (0%)	0 (0%)	—	—	—	0 (0%)
C	0 (0%)	0 (0%)	—	—	—	0 (0%)
D	**9 (100%)**	**9 (100%)**	—	—	—	**18 (100%)**

Table A4.1b. Final Exam. MC

The drawing below represents the same group of galaxies at two different times during the history of the Universe. Use this drawing to answer the following question:

Which one of the following conclusions can you draw about the expansion of the universe from the drawing shown?

a. Galaxy C is the center of the universe.
b. All galaxies move the same amount during the expansion of the universe.
c. Nearby galaxies move more during the expansion of the universe.
d. **All galaxies appear to move away from each other during the expansion of the universe.**



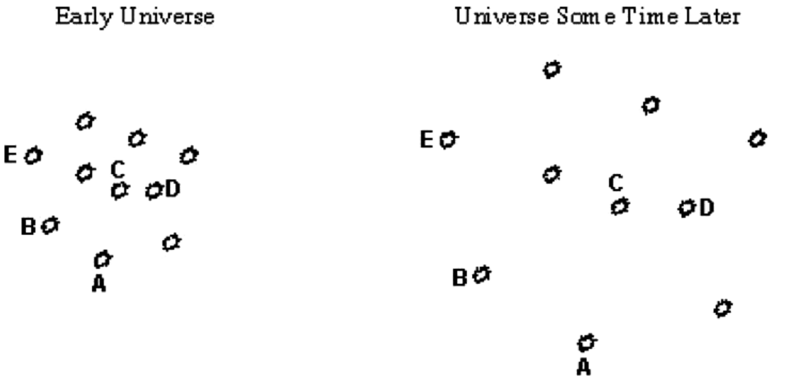
	Fall 2008 N/A	Spring 2009 N/A	Spring 2010 $N = 13$	Fall 2010 $N = 13$	Spring 2011 N/A	Total $KS = 0.06$ $p = 1.00$ $N = 26$
A	—	—	0 (0%)	0 (0%)	—	0 (0%)
B	—	—	1 (8%)	0 (0%)	—	1 (4%)
C	—	—	0 (0%)	0 (0%)	—	0 (0%)
D	—	—	**12 (92%)**	**13 (100%)**	—	**25 (96%)**

Table A4.2. Exam 3. MC

The drawing below represents the same group of galaxies at two different times during the history of the Universe. Use this drawing to answer the following question:

For an observer in galaxy B, which of the following rankings lists the speeds (from fastest to slowest) at which galaxies A, C, and D would be moving away?

a. A > C > D
b. D > A > C
c. C > D > A
d. **D > C > A**



	Fall 2008 ***N*** **= 9**	**Spring 2009** ***N*** **= 9**	**Spring 2010** **N/A**	**Fall 2010** **N/A**	**Spring 2011** **N/A**	**Total** ***KS*** **= 0.26** ***p*** **= 0.79** ***N*** **= 18**
A	0 (0%)	2 (22%)	—	—	—	2 (11%)
B	2 (22%)	0 (0%)	—	—	—	2 (11%)
C	2 (22%)	0 (0%)	—	—	—	2 (11%)
D	**5 (56%)**	**7 (78%)**	—	—	—	**12 (67%)**

Table A4.3a. Exam 3

v1. Galaxy X is measured to have a bigger cosmological redshift than Galaxy Y. Which galaxy is farther away?
X / Y

v2. Galaxy C is measured to have a smaller cosmological redshift than Galaxy D. Which galaxy is farther away?
C / **D**

	Fall 2008 **N/A**	**Spring 2009 (v2)** ***N*** **= 9**	**Spring 2010** **N/A**	**Fall 2010 (v1)** ***N*** **= 13**	**Spring 2011 (v1)** ***N*** **= 13**	**Total** ***H*** **= 4.94** ***p*** **= 0.08** ***N*** **= 35**
C	—	**4 (44%)**	—	**9 (69%)**	**13 (100%)**	—
W	—	5 (56%)	—	4 (31%)	0 (0%)	—
NR	—	0 (%)	—	0 (%)	0 (0%)	—

Table A4.3b. Final Exam
v1. Galaxy X is measured to have a bigger cosmological redshift than Galaxy Y. Which galaxy is farther away?
X / Y
v2. Galaxy C is measured to have a smaller cosmological redshift than Galaxy D. Which galaxy is farther away?
C / **D**

	Fall 2008 **N/A**	**Spring 2009** **N/A**	**Spring 2010 (v2)** $N = 13$	**Fall 2010 (v2)** $N = 13$	**Spring 2011 (v2)** $N = 13$	**Total** $H = 0.38$ $p = 0.83$ $N = 39$
C	—	—	**7 (54%)**	**9 (69%)**	**10 (77%)**	**26 (67%)**
W	—	—	6 (46%)	3 (23%)	0 (0%)	9 (23%)
NR	—	—	0 (0%)	1 (8%)	3 (23%)	4 (10%)

A5. AGE OF THE UNIVERSE

Table A5.2. Exam 3. MC
Based on observations of the universal expansion, the age of the universe is about

a. 14 million years
b. 14,000 years
c. **14 billion years**
d. 14 trillion years

	Fall 2008 $N = 12$	**Spring 2009** $N = 9$	**Spring 2010** $N = 17$	**Fall 2010** $N = 14$	**Spring 2011** **N/A**	**TOTAL** $H = 1.06$ $p = 0.77$ $N = 52$
A	1 (8%)	0 (0%)	0 (0%)	0 (0%)	—	1 (2%)
B	0 (0%)	0 (0%)	0 (0%)	1 (7%)	—	1 (2%)
C	**11 (92%)**	**9 (100%)**	**15 (88%)**	**13 (93%)**	—	**48 (92%)**
D	0 (0%)	0 (0%)	2 (12%)	0 (0%)	—	2 (4%)

Table A5.3a. Exam 3. Essay question
Part 1. What is the approximate age of the universe?
Correct if answer given is between 13 and 15 billion years old.

	Fall 2008 **N/A**	**Spring 2009** $N = 9$	**Spring 2010** $N = 11$	**Fall 2010** $N = 10$	**Spring 2011** $N = 13$	**TOTAL** $H = 0.67$ $p = 0.88$ $N = 44$
C	—	**9 (100%)**	**9 (75%)**	**8 (80%)**	**11 (84%)**	**37 (84%)**
I	—	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
P	—	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
W	—	0 (0%)	2 (25%)	2 (20%)	1 (8%)	6 (14%)
T	—	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
NS	—	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
NR	—	0 (0%)	0 (0%)	0 (0%)	1 (8%)	1 (2%)

Table A5.3b. Final Exam. Essay question

Part 1.What is the approximate age of the universe?

Correct if answer given is between 13 and 15 billion years old.

	Fall 2008 N/A	**Spring 2009** $N = 9$	**Spring 2010** $N = 13$	**Fall 2010** $N = 13$	**Spring 2011** $N = 13$	**TOTAL $H = 2.74$** $p = 0.43$ $N = 48$
C	—	**9 (100%)**	**9 (69%)**	**12 (92%)**	**9 (69%)**	**39 (81%)**
I	—	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
P	—	0 (0%)	0 (0%)	1 (8%)	0 (0%)	1 (2%)
W	—	0 (0%)	4 (31%)	0 (0%)	3 (23%)	7 (15%)
T	—	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
NS	—	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
NR	—	0 (0%)	0 (0%)	0 (0%)	1 (8%)	1 (2%)

Table A5.4a. Exam 3. Essay question

Part 2

v1. How do we know the age of the Universe? i.e. Describe the measurements and calculations you would use to determine it. (Hint: how would we tell if it's older vs. younger?)

v2. How do we know the age of the Universe? i.e. Describe the measurements and calculations you would use to determine it. (Hint: Think about the Hubble's Law Lab: How did you determine the Hubble constant? How can you use the Hubble constant to determine the age of the Universe? Also, think about how you could tell if it's older vs. younger?)

	Fall 2008 N/A	**Spring 2009 (v1)** $N = 9$	**Spring 2010 (v1)** $N = 12$	**Fall 2010 (v1)** $N = 10$	**Spring 2011 (v2)** $N = 13$	**TOTAL $H = 6.44$** $p = 0.11$ $N = 44$
C	—	**0 (0%)**	**0 (0%)**	**0 (0%)**	**0 (0%)**	**0 (0%)**
I	—	4 (44%)	3 (25%)	7 (70%)	7 (54%)	21 (48%)
P	—	2 (22%)	0 (0%)	1 (10%)	1 (8%)	4 (9%)
W	—	0 (0%)	0 (0%)	1 (10%)	1 (8%)	2 (4.5%)
T	—	0 (0%)	1 (8%)	0 (0%)	1 (8%)	2 (4.5%)
NS	—	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
NR	—	3 (33%)	8 (67%)	1 (10%)	3 (23%)	15 (34%)

Table A5.4b. Final Exam. Essay Question

Part 2

v1. How do we know? i.e. Describe the measurements and calculations you would use to determine it. (Hint: how would we tell if it's older vs. younger?)

v2. How do we know? i.e. Describe the measurements and calculations you would use to determine it. (Hint: Think about the Hubble's Law Lab: How did you determine the Hubble constant? How can you use the Hubble constant to determine the age of the Universe? Also, think about how you could tell if it's older vs. younger?)

	Fall 2008 N/A	**Spring 2009 (v1)** $N = 9$	**Spring 2010 (v1)** $N = 13$	**Fall 2010 (v1)** $N = 13$	**Spring 2011 (v2)** $N = 13$	**TOTAL $H = 1.75$** $p = 0.63$ $N = 48$
C	—	**0 (0%)**	**0 (0%)**	**0 (0%)**	**0 (0%)**	**0 (0%)**
I	—	5 (56%)	5 (39%)	8 (62%)	9 (69%)	27 (56%)
P	—	2 (22%)	2 (15%)	2 (15%)	0 (0%)	6 (12%)
W	—	0 (0%)	2 (15%)	1 (8%)	1 (8%)	4 (8%)
T	—	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
NS	—	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
NR	—	2 (22%)	2 (15%)	4 (31%)	3 (23%)	11 (23%)

Table A5.5. Exam 3. T/F

The faster the rate of expansion, the older the age of the universe. T / **F**

	Fall 2008 N/A	**Spring 2009** N/A	**Spring 2010** N/A	**Fall 2010** $N = 13$	**Spring 2011** $N = 13$	**TOTAL** $KS = 0.27$ $p = 0.64$ $N = 26$
T	—	—	—	3 (23%)	6 (46%)	9 (25%)
F	—	—	—	**9 (69%)**	**7 (54%)**	**16 (62%)**
NR	—	—	—	1 (8%)	0 (0%)	1 (3%)

Table A5.6a. Exam 3. FIB

v1. The slower the rate of expansion, the **older** the age of the universe.

v2. The faster the rate of expansion, the **younger** the age of the universe.

	Fall 2008 (v1) $N = 9$	**Spring 2009 (v2)** $N = 9$	**Spring 2010 (v1)** $N = 12$	**Fall 2010** N/A	**Spring 2011** N/A	**TOTAL** $H = 0.16$ $p = 0.92$ $N = 30$
C	**5 (56%)**	**6 (67%)**	**8 (67%)**	—	—	**19 (63%)**
W	4 (44%)	3 (33%)	3 (25%)	—	—	10 (33%)
NR	0 (0%)	0 (0%)	1 (8%)	—	—	1 (3%)

Table A5.6b. Final Exam. FIB

v1. The slower the rate of expansion, the **older** the age of the universe.

v2. The faster the rate of expansion, the **younger** the age of the universe.

	Fall 2008 (v1) $N = 10$	**Spring 2009** N/A	**Spring 2010** N/A	**Fall 2010** N/A	**Spring 2011 (v1)** $N = 13$	**TOTAL** $KS = 0.14$ $p = 0.99$ $N = 23$
C	**6 (60%)**	—	—	—	**8 (62%)**	**14 (61%)**
W	4 (40%)	—	—	—	5 (38%)	9 (39%)
NR	0 (0%)	—	—	—	0 (0%)	0 (0%)

A6. HISTORY OF THE UNIVERSE

Table A6.1a. Exam 3. Essay Question

Q: Briefly describe 4 cosmologically important events in the history of the Universe. For each event, give the approximate age of the Universe and what conditions were like then. (Do NOT include events specific only to Earth, such as the appearance of dinosaurs).

	Fall 2008 *$N = 8$*	**Spring 2009** *$N = 8$*	**Spring 2010** *$N = 12$*	**Fall 2010** *$N = 10$*	**Spring 2011** *$N = 13$*	**Total $H = 0.21$** *$p = 0.97$ $N = 43$*
C	**1 (13%)**	—	**0 (0%)**	**0 (0%)**	**0 (0%)**	**1 (2%)**
I	1 (13%)	—	5 (42%)	5 (50%)	6 (46%)	17 (39%)
P	6 (75%)	—	6 (50%)	4 (40%)	6 (46%)	22 (51%)
W	0 (0%)	—	0 (0%)	0 (0%)	0 (0%)	0 (0%)
T	0 (0%)	—	0 (0%)	0 (0%)	0 (0%)	0 (0%)
NS	0 (0%)	—	0 (0%)	0 (0%)	0 (0%)	0 (0%)
NR	0 (0%)	—	1 (8%)	1 (10%)	1 (8%)	3 (7%)

Reasons for "P": 64% (14 of 43) had incorrect timing. 36% (8 of 43) had incorrect description(s). Time errors:

- BBN began after millions of years (1 student).
- CMB emitted after billions of years (2 students).
- CMB emitted after only minutes (1 student).
- CMB emitted at a few light years (1 student).
- 1st galaxies formed within minutes (6 students).
- 1st galaxies formed within thousands of years (3 students).
- 1st galaxies formed after billions of years (4 students).

Table A6.1b. Final Exam. Essay Question

Q: Briefly describe 4 cosmologically important events in the history of the Universe. For each event, give the approximate age of the Universe and what conditions were like then. (Do NOT include events specific only to Earth, such as the appearance of dinosaurs).

	Fall 2008 **$N = 10$**	**Spring 2009** **$N = 8$**	**Spring 2010** **NA**	**Fall 2010** **NA**	**Spring 2011** **NA**	**Total $KS = 0.18$** **$p = 0.98$ $N = 18$**
C	**3 (30%)**	**0 (0%)**	—	—	—	**3 (17%)**
I	2 (20%)	2 (25%)	—	—	—	4 (22%)
P	4 (40%)	6 (75%)	—	—	—	10 (55%)
W	0 (0%)	0 (0%)	—	—	—	0 (0%)
T	0 (0%)	0 (0%)	—	—	—	0 (0%)
NS	0 (0%)	0 (0%)	—	—	—	0 (0%)
NR	1 (1%)	0 (0%)	—	—	—	1 (6%)

Reasons for 'P': 63% (5 of 18) had incorrect timing. 37% (3 of 18) had incorrect description(s). Time errors:

- 1st galaxies formed within minutes (2 students).
- 1st galaxies formed after billions of years (2 students).
- Solar System formed after millions of years (1 student).

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