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A Multi-Institutional Investigation of Students' Preinstructional Ideas About Cosmology

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Abstract

In order to improve instruction in introductory astronomy, we are investigating students' preinstructional ideas about a number of cosmology topics. This article describes one aspect of this large research study in which 1270 students responded to a subset of three questions each from a larger set of questions about the following areas: definition of a light-year and the structure, composition, and evolution of the Universe. Within structure, we investigated students' ideas about definitions or descriptions of Solar System, Galaxy, Universe, and the relationships among them. Composition included the formation of chemical elements, dark matter, and dark energy, while evolution focused on the Big Bang Theory, age of the Universe, and how the Universe changes over time. Responses were iteratively coded for common themes. Major findings demonstrate that students commonly misidentify the light-year as a measurement of time, and that they provide incomplete definitions of common objects (Solar System, Galaxy) and the Universe itself, often conflating the terms. Generally speaking, students have little understanding of dark matter or dark energy, providing definitions that are superficial or do not answer the question. Consistent with previous research, we found students view the Big Bang as an explosion. Students' ideas about the age of the Universe range from millions to trillions of years, but some students believe the Universe to be infinitely old. For both the age of the Universe and the Big Bang Theory, students are not familiar with the scientific evidence that exists, and in some cases do not believe such evidence can exist. Finally, students' understanding of how the Universe changes over time is based largely on smaller changes of objects within it (e.g., stellar evolution) or the motions of objects (e.g., planetary orbits). These and other ideas provide fodder—both scientifically accurate and inaccurate—on which to build effective instruction. Particular attention should be paid to areas in which words that are used differently between our everyday vernacular and scientific language can create or reinforce alternative conceptions.

1. INTRODUCTION AND PURPOSE

Through observations and measurements of distant supernovae, field galaxies, galaxy clusters, the cosmic microwave background (CMB), abundances of light elements, gravitational lensing, and more, we can answer fundamental questions about the composition of the Universe, its geometry, its age, how structures are distributed and formed, and even the fate of the Universe. Astronomers have measured cosmological parameters such as the Hubble constant (e.g., Freedman *et al*. 2001) and density parameter (Ω; e.g., de Bernardis *et al*. 2000; Spergel *et al*. 2003) to unprecedented precision. Beyond that, detailed observations have revealed some of the properties of the dark matter that comprises more than 80% of all matters in the Universe (e.g., Massey *et al*. 2007; Rubin and Ford 1970). Most astounding of all, it appears likely that 70% of the energy in the Universe is not composed of matter of any sort. Rather, it is made of an as yet unknown quantity that is causing space itself to fly apart at an ever-increasing rate (Perlmutter *et al*. 1998; Riess *et al*. 1998).

As the field of cosmology progresses, astronomers want to share new understandings with our students. Additionally, some members of the astronomy education community have called for an increased use of modern topics within our introductory courses in order to maintain students' interest in the field (e.g., Pasachoff 2002). Undergraduate astronomy courses, however, have had difficulty staying current with rapidly unfolding cosmological knowledge. According to a survey by Bruning (2006a, 2006b), only ∼20% of a typical introductory astronomy textbook is devoted to cosmological topics.

Simultaneously, advances in our understanding of how students learn new content compel us to approach teaching in a way that is different from the lecture-dominated classes of the past. As part of the foundation for creating innovative cosmology curriculum (Coble *et al*., in press; Coble *et al*. 2012), we are conducting research on students' ideas about topics such as the structure, composition, and evolution of the Universe, and (in future research) the physical principles that govern it. This article will describe the research on students' preinstructional understandings, as identified through a large number of student-supplied response (SSR) surveys (also known as open-response or open-ended questions). Students predominantly from introductory undergraduate astronomy courses for general education (hereafter called "ASTRO 101") at multiple institutions provided responses to these surveys on the first or second day of class. Such surveys provide us with insights into the ideas students bring to our ASTRO 101 courses so that we may build upon, and where necessary work to facilitate change in, their understanding of cosmology.

2. BACKGROUND

2.1. Conceptual Framework

Research in cognitive science, science education, and educational psychology has demonstrated that students develop ideas about the world from an early age (Bransford, Brown, and Cocking 1999). For example, infants as young as 3–6 months appear to understand that unsupported objects will fall to the ground, and their observation of objects is different when the situation seems to violate this pattern (such as when the infant is unable to see the existing support structure). Interactions with the natural world and other people, earlier in-school and out-of-school learning, and popular media all contribute to the base of ideas that our students bring with them to our classes.

The most effective learning, then, takes place when this existing understanding is used as the basis for developing new ideas (Bransford, Brown, and Cocking, 1999; Donovan and Bransford 2005). Instructors need to help students see the connections between their existing knowledge and new content. There are a number of different instructional strategies through which such connections can be made during instruction—*Lecture-Tutorials* (Prather *et al*. 2007), *Peer Instruction*-style questions (Green 2003; Mazur 1997), and "Elby pairs" in physics (Elby 2001) are just a few examples—however, an in-depth discussion is beyond the scope of this article. By examining preinstructional ideas, we can have an inkling of the notions that students may possess, even if we do not have the resources to investigate the details of each individual student's knowledge.

2.2. Previous Research on Cosmological Topics

The identification of students' ideas about the world has a rich history that goes back a century, with significant progress made following the work of Piaget in the 1950s and 1960s. Within astronomy, there has been an emphasis on observational topics about which people may develop ideas naturally (e.g., lunar phases, day/night, seasons; see Bailey and Slater 2003; Lelliott and Rollnick 2010; and references therein). However, there has been little research on cosmological topics to date. Since this is an active area of significant astronomical research that can garner attention in the media and may be of greater appeal to students in our ASTRO 101 courses, we should attempt to understand this area within astronomy education research as well.

Prather, Slater, and Offerdahl (2002) surveyed nearly 1000 students in middle school, high school, and ASTRO 101 courses about their understanding of the Big Bang. Most students indicated that they had heard of the Big

Bang theory (56%, 86%, and 94% for middle school, high school, and college, respectively), with a noticeable increase in this number between middle school and high school. Of those who had heard of this theory, a quarter to half (increasing with grade) indicated that the theory describes the creation of the Universe, while another quarter to more than a third (here decreasing with grade) said it relates to the creation of planetary systems. Responses from the remaining 21%–36% (again decreasing with grade) were categorized as "other" by the authors. Prather, Slater, and Offerdahl (2002) noted that within the creation of the Universe category, from 62% to 80% (increasing with grade) believed the Big Bang to be an explosion that distributed or arranged pre-existing matter, and suggested that this might result from a fundamental belief of "you can't make something from nothing."

As part of a larger study, Wallace, Prather, and Duncan (2012) surveyed more than 2300 ASTRO 101 students across multiple courses over 3 semesters, prior to instruction. Major topics under investigation included, e.g., expansion and evolution of the Universe, the "Hubble plot" demonstrating the expansion of the Universe, and dark matter in spiral galaxies. As had been seen by Prather, Slater, and Offerdahl (2002), the most common misconception about the Big Bang was that it was an explosion (more than 50% of responses), with approximately a third of the respondents indicating some kind of existing matter. Few students understood the nature of the expanding Universe or connected the observed expansion with the Big Bang. Many students were unable to correctly choose from a selection of Hubble plots to indicate different expansion descriptions (expanding at a constant rate, contracting at a constant rate, expanding at an accelerating rate, or expanding at a decelerating rate). Finally, when asked about the nature of rotation curves for spiral galaxies, few students said anything about dark matter prior to instruction (and often identified incorrect graphs as their choice for how a galaxy's motion can be represented).

Another important aspect of cosmology education research relates to students' understanding of large timescales—including the age of the Universe and when major events occurred. Most of the research in this area comes from geoscience education and, accordingly, focuses on Earth's history (Grundstrom, Slater, and Stassun 2008), although work by Trend (1998, 2000, 2001a, 2001b) includes the Big Bang as one of the events on the timeline used.

Finally, others have included cosmology topics as part of multi-topic studies. Both Comins (n.d.) and Philips (1991) include "the Universe is static (unchanging)" as common misconceptions. Simonelli and Pilachowski (2003) noted that approximately 15% of surveyed ASTRO 101 students said the Solar System is formed out of the Big Bang, an idea that has also been observed in geoscience education research (e.g., Libarkin, Kurdziel, and Anderson 2007; Marques and Thompson 1997). Pimbblet (2002) suggests that effective teaching of cosmological topics requires attention to both the evidence for the Big Bang (specifically the Hubble expansion and the cosmic microwave background radiation) and the cultural (including religious) beliefs of the students.

Research in cosmology education to date has focused primarily on the nature of the Big Bang, with newer studies also investigating students' ideas about expansion and age of the Universe. However, much work remains to be done if we want to understand the range and frequency of student understanding about cosmological topics.

2.3. Research Questions

After reviewing the literature and identifying the goals of our curriculum development project (Coble *et al*., in press), we embarked on a research program to further investigate students' understanding about cosmology. This multiphase program includes (1) broadly investigating students' preinstructional beliefs about cosmology topics while (2) also looking at a subset of ASTRO 101 classes from a single institution in depth, including data from interviews with students and class artifacts, such as homework assignments and unit and final exams. The in-depth studies are reported in two companion pieces to this article (Coble *et al*.; Trouille *et al*.).

This article will focus on the multi-institutional study of students' preinstructional ideas. The overarching research question driving this component of our program is: What is the nature and frequency of students' preinstructional ideas about topics relating to cosmology, specifically areas involving the structure, composition, and evolution of the Universe?

3. METHODS

The methods of this study mirror those of previous research on students' understandings of astronomical topics (e.g., Bailey *et al*. 2009; Prather, Slater, and Offerdahl 2002). We asked questions of undergraduate students through open-response surveys and analyzed the responses through an iterative process of open coding. The details of the methods are described further in the sections below.

3.1. Setting and Participants

Over the period Spring 2009–Spring 2012, 15 ASTRO 101 and 2 introductory cosmology courses that satisfy general education requirements participated in this project. Courses were offered at five different institutions from across the country, including an urban community college, a regional Christian college, an urban minority-serving university, a regional state college, and an urban research-intensive university. Surveys were completed anonymously and no demographic data were collected other than enrollment in prior astronomy coursework; however, the instructors of the courses believe that the populations within each course were approximately representative of their school's broader demographics.

We have responses from 1270 students, most of whom responded to only one of the survey forms (number of respondents, N, for each question will be described in Section 4). In regards to previous coursework, 10.8% of the students reported they had taken astronomy prior to the course in which they were responding to the survey (with 7.6% of the total at the college level and 2.4% having had astronomy prior to college; 0.7% did not indicate at which level). Sixty-two percent (62.6%) said they had not previously taken astronomy and 26.6% did not answer the question.

3.2. Data Collection Instruments

The data that were collected for this study consisted of written answers on a SSR survey. Each survey contained a question about prior astronomy coursework and two or three content questions (some of which had multiple parts). In each administration, we used two or three different forms, each containing somewhat different questions. Each form (see Table 1) was photocopied on different colors of paper and then mixed, in order to be randomly distributed to the participants. In most cases, a given student responded to only one of the SSR forms used in their class. For one particular class, each of the 26 students completed all three of the forms given.

Questions were created by the first two authors (a science education researcher and a cosmologist) and reviewed by the co-authors and colleagues from the larger research project. In all semesters, we developed questions that addressed the topic in slightly different ways (for example, see the three questions on the light-year on forms D, E, and F). We attempted to create questions that were strongly worded and unambiguous, avoiding jargon whenever possible (DeVellis 2003). These efforts during question development contributed to the content validity of the questions (Creswell 2007).

Individual questions are identified throughout this article by their form letter and the question number—i.e., D2 refers to form D, question 2—as listed in Table 1. This article will focus on the results from questions about the definition of the light-year (D2, E2, F2), the structure of the Universe (A*1, B*1, A1, B*2), the composition of the Universe (A*2, A2, C2), the Big Bang (A*3, C1), the age of the Universe (B*3, B2), and the evolution of the Universe over time (B*2, B1). Questions on the shape/curvature of the Universe (D1, E1), the fate of the Universe (E3, F1), and black holes (D3, F3) will be discussed in a future article.

Questions on the SSR surveys evolved over the semesters to reflect insights and new areas of interest after analysis of earlier data. For example, our original forms (identified here by A* and B*) were edited into forms A, B, and C as a result of the initial analysis on the Spring 2009 data. Specifically, we found that in Spring 2009 (questions A*1 and B*1 in particular), participants skipped many of the details in these lengthy questions. Subsequently, we broke up the question into smaller parts (see question A1) or simply edited out some of the details. Major topic changes are reflected by new forms (D, E, and F) in later semesters.

Surveys were given on the first or second day of class, prior to any instruction about astronomy topics. Depending upon the instructor's preference, the SSR surveys may have been given prior to or after discussion of the syllabus and course requirements. Students were asked to share their understanding of the questions on their form, giving their best guess even if they were not sure of the "correct" answer. They were also assured that the surveys were to be answered anonymously (no names were collected) and would in no way affect their grades in the course.

Table 1. The SSR survey questions

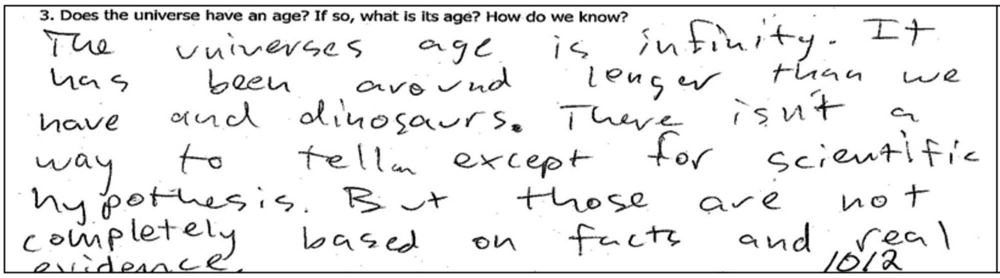
Form	Spring 2009 Questions
A*	1. Describe each of the following: Galaxy, Constellation, Solar System, Universe. Are any of these related? If so, how? 2. Explain where and how the chemical elements were formed. Is there stuff in the Universe that is not made of the chemical elements? If so, describe. 3. Explain the Big Bang Theory in your own words. What evidence supports it?
B*	1. Provide a description of the objects you think are in the Universe today and how they are arranged. Be as specific as possible, including the sizes and distances between these objects. (Feel free to include a sketch if this helps you to explain.) 2. Describe what the word "Universe" means. Does the Universe change over time? If so, how? 3. Does the Universe have an age? If so, what is its age? How do we know?
Form	**Fall 2009–Spring 2011 Questions**
A	1. Describe each of the following terms: (a) Galaxy: (b) Solar System: (c) Universe: (d) Describe any relationships that may exist among any of these three things. 2. Explain where and how the chemical elements were formed. If you think there is anything in the Universe that is not made of the chemical elements, please describe that too.
B	1. Describe how you think the Universe changes over time, if at all. 2. Think about how long the Universe has existed and answer the following: (a) Does the Universe have an age, or has it always existed? (b) How do we know? (c) If you think the Universe has an age, what is its age?
C	1. Think about the Big Bang Theory and answer the following: (a) Explain the Big Bang Theory in your own words. (b) Describe what evidence you think supports the Big Bang theory. 2. Describe what you think the following terms mean: (a) Dark matter: (b) Dark energy:
Form	**Fall 2011–Spring 2012 Questions**
D	1. What do astronomers mean when they talk about the "shape" or "curvature" of space (the Universe)? How do they measure this trait? 2. Which of the following best describes a "light-year"? (a) A unit to describe astronomical distances (b) A unit to describe astronomical time scales (c) The speed of light Why did you select the answer you chose? 3. What is a black hole?
E	1. Which of the following best describes the "geometry" or "curvature" of space (the Universe)? (a) Round (the Universe overall is spherically curved or close to it) (b) Flat (the Universe overall is not curved but flat in all three dimensions) (c) Hyperbolic (the Universe overall is saddle shaped) (d) Some other curvature—*please specify* (e) There is no way to know Why did you select the answer you chose? 2. What is a light-year? How is it used in astronomy? 3. What is the long-term fate of the Universe? How do we know?
F	1. Is the Universe "open" or "closed"? What do astronomers mean when they use these terms? 2. What is a light-year? How is it used in astronomy? 3. What does it mean to say that a "no light can escape" from a black hole?

Table 2. **An example of thematic codes from analysis of question(s) B*3 and B2**

Description: Does the Universe have an age?		**Evidence[a]: How do we know the age of the Universe?**	
Y	Yes	BB	Big Bang
N	No	CD	Carbon dating, fossils, radiation
AE	Always existed/infinite	Class	Authority (know from class, scientists, etc.)
		CMB	Cosmic microwave background radiation
Age: What is the age of the Universe?		EB	Everything has a beginning
1	$<20\,000$ years	Est	Estimated
2	20 000 to $<10^6$ years	Exp	Expansion
3	10^6 to $<10^9$ years/millions	LBT	Lookback time, light travel time
4	10^9 to $<10^{12}$ years/billions[b]	Math	Math, computers, algorithms, models
5	$13–15 \times 10^9$ years old[b]	Obj	Find age of objects (planets, stars, etc.)
6	$>10^{12}$ (trillions)	Rate	Rate/how objects have changed over time
7	Descriptive, no numbers	Th	"Just a theory," no proof, no evidence
Unk	Yet unknown to scientists	WH	Written history
NA/IN	Not applicable/infinite	Other	Seasons, Olber, etc.
Codes common across all questions			
CK	Cannot know	NR	No response
DK	I do not know	NS	Nonscientific response

[a] Note that these are the students' ideas about evidence, and not necessarily what astronomers would consider evidence for the age of the Universe.

[b] The range $13–15 \times 10^9$ years, close to the currently accepted value of 13.7×10^9 years, was distinguished from those that provided other numbers (e.g., 20, 100×10^9 years) or that used only the term "billions" without an associated numerical value.



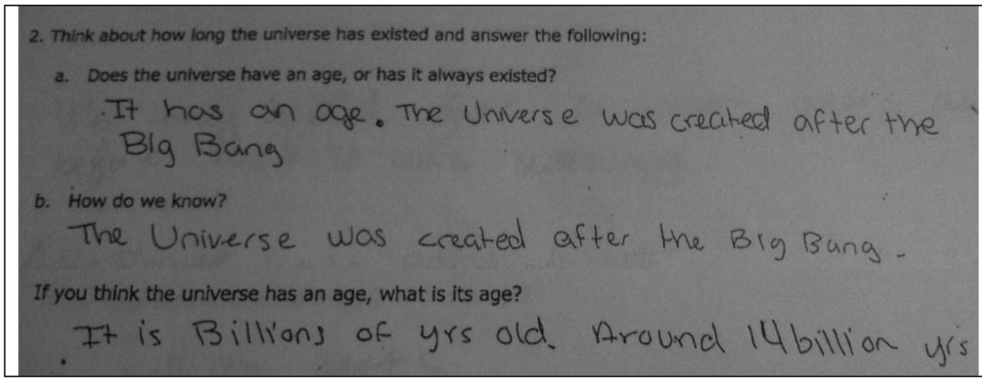
3. Does the universe have an age? If so, what is its age? How do we know?

The universes age is infinity. It has been around longer than we have and dinosaurs. There isn't a way to tell except for scientific hypothesis. But those are not completely based on facts and real evidence. 1012

#1012

Description: AE
Age: NA/IN, 7
Evidence: Th, CK

Figure 1. Response to question B*3 from #1012, Description: AE; Age: NA/IN, 7; Evidence: Th, CK.



2. Think about how long the universe has existed and answer the following:

a. Does the universe have an age, or has it always existed?

It has an age. The Universe was created after the Big Bang

b. How do we know?

The Universe was created after the Big Bang.

If you think the universe has an age, what is its age?

It is Billions of yrs old. Around 14billion yrs

#8026

Description: Y
Age: 5
Evidence: BB

Figure 2. Response to question B2 from #8026, Description: Y; Age: 5; Evidence: BB.

3.3. Data Analysis Procedures

We analyzed the SSR surveys in an iterative, constant comparative process of open coding to identify themes that emerged from the set of responses, consistent with grounded theory (Creswell 2007; Glaser and Strauss 1967). Responses to a given question were read by at least two researchers; each researcher independently recorded common themes seen in the responses. This process was repeated until no new themes emerged and the resulting list was considered comprehensive. The researchers then compared their themes and reached agreement on the final list to be used. Each theme was next assigned a short code and codes were grouped where appropriate. Some of the themes were consistent across different questions; conversely, some themes were exclusive to a particular question. Whenever themes could be used for multiple questions, care was taken to use the codes consistently across all versions of the questions and their responses, thus increasing the reliability of the coding scheme (Creswell 2007).

Multiple researchers then read each participant's response and assigned one or more codes as appropriate. An individual response could be coded for multiple themes, and this was often the case, especially for lengthier responses. The researchers reviewed their initial coding of the responses and compared them with one another. Because there was a large number of codes that could be present or not—rather than a single rubric score as is sometimes used for open-response questions—we did not attempt to calculate an interrater reliability such as κ. However, our estimate is that the researchers initially agreed on approximately 80%–85% of the survey responses. This suggests good reliability of the coding scheme developed (Creswell 2007). For those responses on which the codes differed between researchers, the selections were discussed and negotiated as needed to come to 100% agreement on the final codes to be assigned. Codes were recorded on each SSR survey as well as documented in a spreadsheet. The frequency of the presence of each code was determined.

Finally, the validity of the survey coding and interpretation was established primarily through the use of a multimember research team, including both the authors of this article and other members of the larger project who were not directly involved in the research project. Coding by at least two members of the author team ensured a common understanding of the responses themselves as well as our interpretations of them. Other members of the project served as peer debriefers (Creswell 2007) who reviewed aspects of the study at various points in time, contributing to the credibility of the interpretations.

3.4. Example of Thematic Coding and Application to Responses

An example of the codes and sample participant responses may help to illustrate the thematic coding process. Questions B*3 and B2 (see Table 1) ask students to discuss the age of the Universe. The list of codes that emerged from the responses to these questions is provided in Table 2. Note that in this case, we grouped the codes according to which portion of the question they addressed (i.e., "does the Universe have an age"; "if so, what is the age"; and "how do we know the age").

Figures 1 and 2 show sample student responses to questions B*3 and B2, respectively. In Figure 1, the first statement, "The Universe's [*sic*] age is infinity," results in the code AE for the description category. Appropriately, the age category is assigned NA/IN; however, a code 7 is also used to account for the statement "longer than we have and dinosaurs," as a descriptive but non-numerical explanation. When describing how we know about the Universe's age, this student says, "There isn't a way to tell (coded as CK) except for scientific hypothesis. But those are not completely based on facts and real evidence (coded as Th)." This final category encompasses the kinds of statements that show the student does not understand the nature of scientific theory, hypotheses, and other similar ideas, and particularly the robustness with which such ideas are developed—a common difficulty identified in research about the nature of science (see, e.g., McComas 1996). The response in Figure 2 is one in which a specific age is identified—in this case, 14×10^9 years (the range of $13–15 \times 10^9$ years was coded as 5). This student's answer to part (b) is not really a statement of evidence, but the response ties the age of the Universe to the Big Bang (coded as BB).

4. RESULTS

4.1. Astronomical Distances: Defining a Light-Year

From our experience as instructors, we know that students have difficulty understanding the specialized units used in astronomy. Table A1 provides definitions of *light-year* (and other terms to be discussed in later sections)

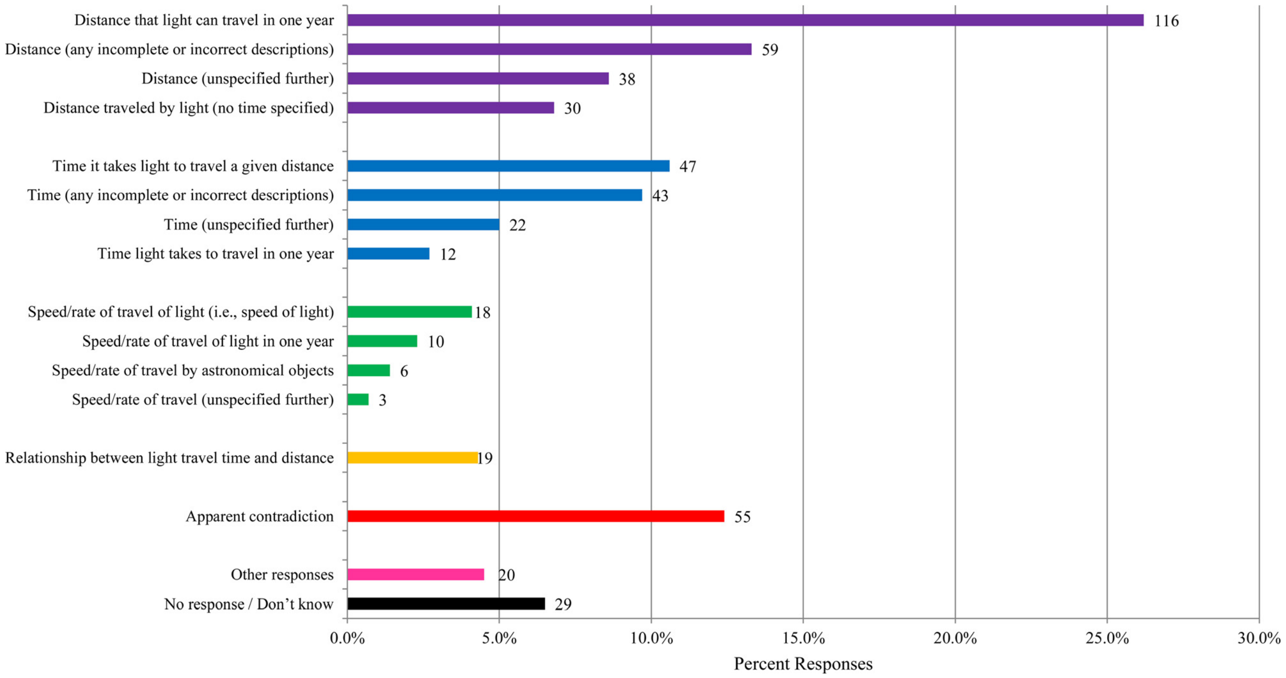


Figure 3. Themes from questions on the definition of a light-year (E2 and F2) ($N = 443$). Labels to the right of each bar indicate the number of responses within the given category.

from the text and/or glossaries of three recent introductory astronomy textbooks. Although the light-year (ly) is a measure of distance, the inclusion of the word "year" means that students may believe it to be a measure of time. Given that astronomers often discuss distances in terms of light's travel time (e.g., Proxima Centauri is 4.2 ly away, or it takes light 4.2 years to travel from Proxima Centauri to us), this is an understandable confusion. But exactly how prevalent are these ideas? Are there other ideas about the light-year that students hold about which we should be aware?

In reviewing the responses to questions E2 and F2 ($N = 443$), we see that there is a large percentage of students who correctly identify a light-year as a measure of distance (54.9%), as well as those who incorrectly identify it as a measure of time (28.0%) or as a speed (8.8%). (As a reminder, the coding of all themes present in a response means the percentages may add to more than 100%.) However, these percentages may be misleading, as responses indicate that students may actually hold more than one of these ideas at the same time. About an eighth (12.4%) of the responses were classified as having an *apparent contradiction* within their ideas; in other words, the response included both distance and time vocabulary but the relationship between the two was unclear or conflated. An example of a response that was classified in this way is, "A light-year is the speed at which light travels. It is used for distance" (#10578). While the student might correctly understand the relationship between light travel time and distance and is simply not expressing it well, it is not clear from this written response, and so the apparent contraction code is applied.

Within these broad categories of distance, time, and speed is a wide range of detail that includes both correct and incorrect elements. Figure 3 presents the major themes that were uncovered in the analysis of this question, along with the number and percentage of responses that were coded for each theme. Note that while more than one category could have been applied to a given response, the details within a larger category (distance, time, speed) are generally exclusive. In other words, a response coded "distance (unspecified further)" would not also be coded one of the "incomplete or incorrect" definitions. The incomplete or incorrect subcategory combines several others of small N (for example, distance between Earth and Moon or distance from Earth to a star).

Question D2 ($N = 220$) also asked about the nature of a light-year, but posed the question in a multiple-choice format with an additional "explain your choice" open-response component. By asking students to explain why they made a certain selection, we may gain insights into their understanding that would not be expressed through other wording choices; it should be noted, however, that the responses provided here would not be analyzed in

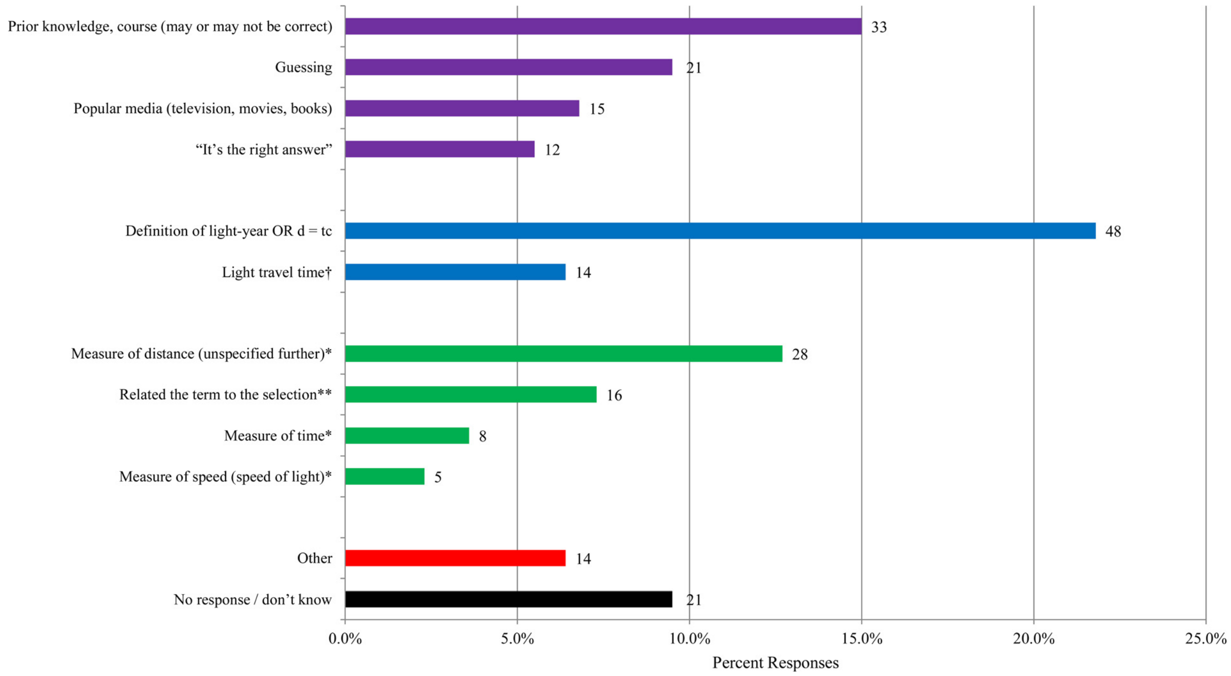


Figure 4. Themes from "explain your selection" on the definition of a light-year multiple-choice question (D2) ($N = 220$). Labels to the right of each bar indicate the number of responses within the given category. †For example, "relates to how long light takes to travel the distance." *In these three categories, responses were not much more than a repeat of the question—no new information was provided. **For example, "'year' or (light) in is the word."

terms of correct or "incorrect." Rather, we hope to learn additional information about why students feel their ideas are justified and where their ideas come from.

In the multiple-choice portion, 70.5% of the students correctly selected that the light-year refers to astronomical distances; 14.5% said it refers to astronomical time scales; 12.7% said it is the speed of light; and 1.4% selected more than one option. When asked to explain why they made the selection they did, participants provided a number of different reasons. Some were generic in nature, such as saying they had learned it previously or had heard it through popular media such as television or movies. Others provided more scientific explanations, such as correctly giving the definition of a light-year (i.e., the distance light travels in 1 year) or stating that the light-year relates to measurement. The themes found in these responses are provided in Figure 4. Note that the "explain your selection" codes are independent of the selection itself; in other words, responses with both correct and incorrect selections could be classified as "prior knowledge" or "it's the right answer," for example.

4.2. Structure of the Universe

One of the first questions on the surveys concerned the relationship between the major structural components of the Universe. Specifically, we wanted to know what students understand about the nature of the Solar System, Galaxy, and Universe, and what relationships exist between those objects. Questions A*1 and B*1 (see Table 1) attempted to pull out students' ideas on this topic during Spring 2009, with $N = 33$ and $N = 52$ students responding to each question, respectively. Initial analysis, however, showed that the questions were too broad to be coded in the way we wanted. For example, in response to question A*1, participants might have described only one or two of the terms and omitted the others; it was not clear whether this was a result of the students not knowing all of the terms, reading the question too quickly, or simply ignoring the instructions. Responses to "Are any of these related" were often simplistic and/or undecipherable. As a result, these questions were rewritten to be more specific and broken down into parts, which in a previous study (Bailey *et al*. 2009) had shown to yield more complete and analysis-friendly responses. The new version of this question, A1 (see Table 1), was answered by $N = 199$ students. We will discuss these responses below.

4.2.1. Defining Structural Components

In question A1(a–c), students were asked to define Galaxy, Solar System, and Universe; these terms are also defined by various textbooks as given in Table A1. It is interesting to notice the different levels of detail in the textbook definitions of Solar System (and that only one of the three books defines this in a generic way to be applied to stars other than the Sun). Neither Chaisson and McMillan (2010) nor Slater and Freedman (2012) provide definitions of star or stellar systems. In the case of galaxy, two of the three definitions focus not only on stars (excluding other components such as gas, dust, or dark matter) but also include that the system is gravitationally bound together. Finally, one of the books does not explicitly define Universe, either in the glossary or within the text.

As participants defined these terms on the SSR surveys, they tended to focus on a superficial level of naming a subset of the objects found within each larger system. For example, the Solar System might be defined as "the Sun and planets," and a galaxy might be described as "millions of stars." Thematic coding turned out to be limited in its usefulness, and so a second level of coding was performed for this question. Responses were classified as either "Reasonable (strong)," in which the response might include multiple components or an indication of a hierarchical relationship (such as orbital motion); "Weak," in which only one or two components are included and/or were too simplistic of a description; "Incorrect or Unclear," containing incorrect components (such as a galaxy inside the Solar System) or a response that could not be interpreted by the researchers; or when left blank, "No Response." A handful of statements, such as those containing joke responses, were classified as "Nonscientific." Table 3 provides the percentages of the four response classifications, as well as an example of each type of response.

4.2.2. *Hierarchical Relationships Between Structural Components*

Anecdotal evidence suggests that students often confuse Solar System and galaxy, or include objects such as stars (which are external to the system) within the definition of Solar System. Thus, question A1(d) asked participants to describe the relationship between the Solar System, Galaxy, and Universe. The simplest reasonable response might look something like, "The Solar System is inside a galaxy, and a galaxy is inside the Universe." This type of explanation does not address any issues relating to size and scale, which we would hope

Table 3. Categorization of SSRs for question A1 ($N = 199$)

	Solar System	Galaxy	Universe	Hierarchical relationship
Reasonable (strong) definition	129 (64.8%)	129 (64.8%)	150 (75.4%)	122 (61.3%)
Examples	"It is the grouping of planets that revolve around a celestial being, e.i. (*sic*) the Sun" (#101-Z002-098)	"A large cluster of millions & billions of stars & planets." (#101-Z002-075)	"Space. Everything and anything in outer space." (#101-Z002-092)	"Solar system is in a galaxy and galaxies are in the Universe" (#101-Z002-084)
"Weak" definition	44 (22.1%)	27 (13.6%)	28 (14.1%)	—
Examples	"The planets" (#101-P002-100)	"Milky Way" (#101-Z002-024)	"Outer space" (#9010)	—
Incorrect or unclear definition	19 (9.5%)	24 (12.1%)	8 (4.0%)	52 (26.1%)
Examples	"The solar system is made of many galaxies" (#8016)	"A particular solar system" (#101-P002-027)	"Galaxy that has planets and stars" (#101-P002-091)	"Galaxies make up the solar systems. The Universe is comprised of many solar systems." (#9007)
No response/ nonscientific	7 (3.5%)	19 (9.5%)	13 (6.5%)	25 (12.6%)

Note: The hierarchical relationship was classified as "reasonable" or "conflated/unclear"—no middle category (weak) was used.

to see after instruction, but it does at least demonstrate a basic understanding of the nature of these three structural components. Responses to this question were categorized in a similar way as question A1(a–c), as "Reasonable but Incomplete," "Incorrect or Unclear," or "No Response/Nonscientific." Percentages of responses within each category are given in Table 3. The most common error that arose in the SSR surveys was, as noted anecdotally, a conflation of galaxy and Solar System (i.e., "the Galaxy is inside the Solar System, which is inside the Universe").

4.3. Composition of the Universe

Another set of questions was designed to uncover students' ideas about the various "stuff" that makes up the Universe. Two versions of a question (A*2 and A2) asked about the origin of chemical elements, as well as whether there is anything in the Universe not made of chemical elements. Questions A*2 and A2 were answered by a total of $N = 251$. Question C2 ($N = 186$) specifically asked participants to define dark matter and dark energy. Textbook definitions for dark matter and dark energy are provided in Table A1.

4.3.1. Chemical Elements

When thinking about the origin of chemical elements, a complete answer would actually require multiple components. Light elements (hydrogen, helium, and lithium) were formed in the early Universe as a result of Big Bang nucleosynthesis, with heavier elements being formed during nuclear fusion inside stars or as the result of supernova explosions. There were no responses that included all three of these components, though each was mentioned in isolation by at least a small portion of the respondents. The Big Bang as the origin of chemical elements was given by 20.7% of the participants, while 4.0% mentioned supernovae (sometimes simply calling this "explosions of stars"). Nuclear fusion, or the creation of elements by/in stars, was mentioned by 6.8%. Another 4.0% of the participants said that elements are formed in chemical reactions. More than half (52.6%) of the participants said they did not know or did not attempt to state where chemical elements are formed.

Few participants attempted the question about whether the Universe contains anything that was not made of chemical elements (83.7% did not know or did not respond to this question). A little less than a tenth (8.8%) of the participants said that everything is, in fact, made of chemical elements. Even fewer responses (7.6%) included one or more examples of something the participant thought was not made of chemical elements. These responses included such ideas as dark matter, energy, and electricity.

4.3.2. Dark Matter

Astronomers currently define dark matter through its ability to gravitationally interact with astronomical objects and its lack of direct observational signatures across the electromagnetic spectrum (Table A1), but we do not yet have a good understanding of its more fundamental nature. Thus, it should not be a surprise that students' ideas about dark matter are, at best, superficial. For question C2, more than a quarter (26.9%) gave no response or said "I don't know," and none of the other response categories stood out as being particularly popular (in fact only one category included more than 10% of the responses). "Matter that is not visible" and similar phrases made up 12.4% of the responses. Black holes accounted for 8.6% of the responses, and space was another 7.5%. A catchall category of "stuff," which included all other material objects not otherwise accounted for, comprised 9.1% of the responses. Antimatter was identified by 6.5% of the respondents, while a generic description such as "black matter" (without further explanation) accounted for another 6.5%. All other categories were each identified in less than 5% of the responses.

4.3.3. Dark Energy

As seen in Table A1, textbook definitions of dark energy are imprecise and, like dark matter, are based on how dark energy interacts rather than its fundamental nature. Dark energy is a yet to be determined form of matter or property of space that is causing the expansion of the Universe to accelerate. Students, not surprisingly, are less familiar with this term than some of the other terms in this study (e.g., light-year, galaxy), as indicated by a full 41.9% not attempting a response. Answers provided were again relatively low frequency, with none greater than 10%. Black holes again made an appearance, found in 7.5% of the responses. Seven percent (7.0%) said that dark energy is "energy from dark matter," while another 5.4% called it "invisible energy." Four percent (3.8%) related dark energy to the expansion of the Universe (though the accuracy of these responses was questionable). This question also garnered the largest percentage of responses (6.5%) classified as “nonscientific”—Darth Vader and Lord Voldemort were particularly popular here.

4.4. Evolution of the Universe

A series of questions were used to investigate students’ understanding of the evolution of the Universe. In questions A*3 and C1, students ($N = 219$) were asked to define the Big Bang and describe what evidence exists for it. Questions B*3 and B2 investigated students’ knowledge of the age of the Universe, as well as how astronomers derive it ($N = 239$). Finally, question B*2 and B1 asked students to describe how the Universe changes over time, if at all ($N = 224$). Cosmologists call the model for how the Universe has changed over time—specifically, how it has expanded and cooled from a hot, dense, early state—the Big Bang Theory. Some astronomers colloquially call the early moments of the Universe’s existence the “Big Bang” (see Table A1). Perhaps this is to emphasize the fact that the Universe sprang into existence a finite time in the past—13.7×10^9 years ago—but in fact the model explains all epochs of time: the past, present, and future of the Universe, not just the earliest moments. Therefore, we will use the phrase Big Bang to mean the theory or explanation for how the Universe changes over time. As we will see, students view this differently than scientists.

4.4.1. Big Bang and Its Evidence

Many of the participants’ responses in this category contained multiple and/or complex ideas that were assigned more than one code. For example, one response might have read along the lines of, “an explosion that created the planets”—this received a code for “explosion” as well as for “formation of planets.” As such, the percentages add to more than 100%.

When asked to define the Big Bang Theory, half (49.8%) of the responses said that it was an explosion of some kind. The majority of participants (85.4%) related the Big Bang Theory to the formation or creation of something. Other responses, which we also saw in our in-depth study (Trouille *et al.*), include that the Big Bang Theory describes the start of the expansion of the Universe (9.1%) or that it was a collision between objects or particles (11.0%). Participants included very little, if any, detail in this question about the evolution of the Universe (such as the Universe beginning as hot but cooling over time) or about the structure of the Universe (e.g., whether the Universe has a center). Figure 5 shows the major themes identified within the definitions, along with the number and percentage of responses for each theme.

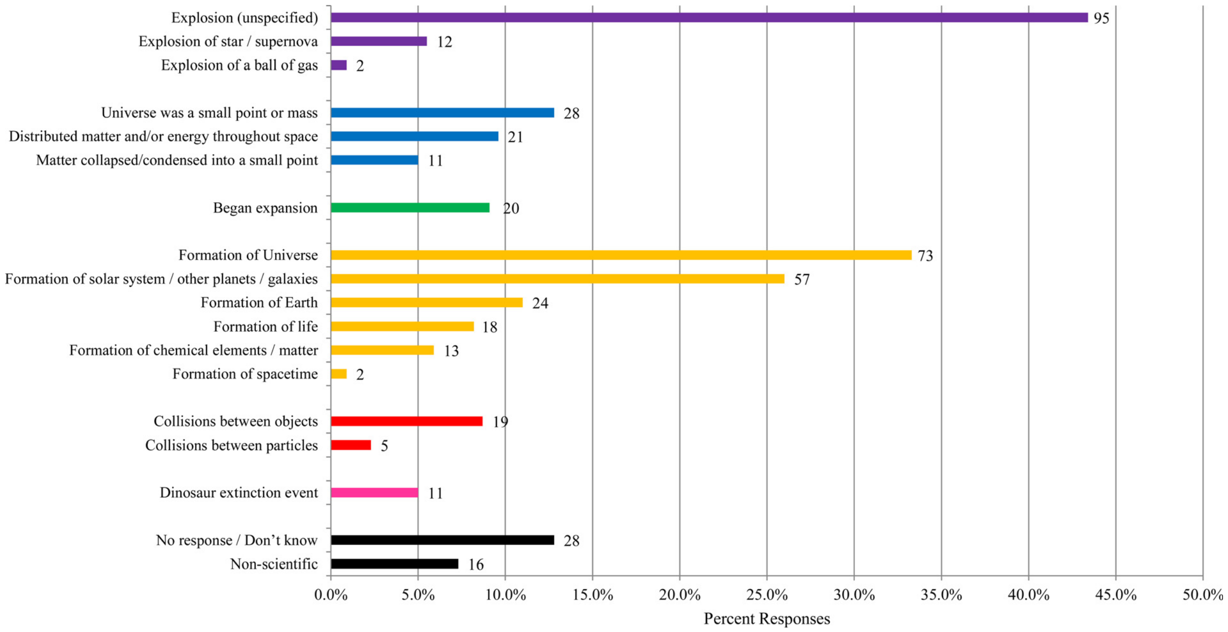


Figure 5. Themes from questions on the definition of the Big Bang Theory ($N = 219$). Labels to the right of each bar indicate the number of responses within the given category.

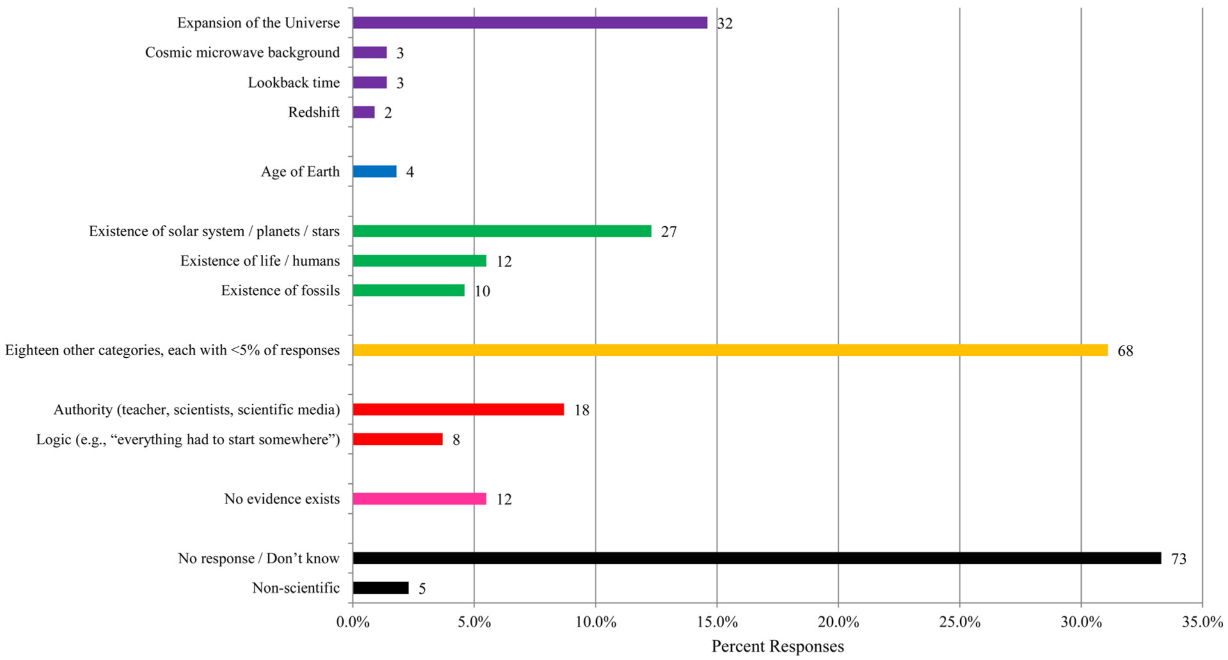


Figure 6. Themes from questions on the evidence for the Big Bang Theory ($N = 219$). Labels to the right of each bar indicate the number of responses within the given category.

In response to the question of evidence for the Big Bang Theory, there are three components we would like to see postinstruction: the expansion of the Universe, the composition of the Universe (i.e., percentage of hydrogen, helium, etc.), and the cosmic microwave background radiation. As can be seen in Figure 6, expansion of the Universe was the dominant evidence cited (14.6% of the total), while the cosmic microwave background radiation was included by only three students (1.4%). No student included the composition of the Universe as evidence (and so of course, none included all three). Another group of students did not attempt to connect evidence in the way we would want them to do after instruction. Rather, 8.7% of the participants used an appeal to authority as the evidence; in other words, they said something such as, "my teacher told me" or "I saw it on the Discovery Channel." Additionally, 5.5% said there is no evidence for the Big Bang Theory. It should also be noted that a much larger portion of the responses (33.3%) were blank or "don't know" for this sub question compared to the definition of the Big Bang Theory. The existence of different objects or organisms (living or extinct) accounted for nearly a quarter of the responses (22.4%).

4.4.2. Age of the Universe

Of the $N = 239$ students who responded to this question (either B*3 or B2, which were coded identically), 59.0% of them said that the Universe has a finite age while 26.4% said the Universe has always existed (or that its age is "infinity"). The remaining 14.6% either did not answer the question or gave a contradictory response, such as "the Universe has always existed; it is billions of years old."

Ages provided by participants covered a very wide range, as shown in Figure 7. The currently accepted value of 13.7×10^9 years old fell into the response category of $13–15 \times 10^9$ years old. Within the "generic descriptors" category were words without any kind of numerical assessment for the age—"very, very old," and "hella old" are responses indicative of this category. Only 2.6% of the responding participants gave an age for the Universe that was 20 000 years old or younger, suggesting that literal interpretations of religious doctrines may not have been a major factor for the majority of these students, or that if it was, they chose not to share those beliefs within their responses on this survey completed in a science course. Finally, 28.5% of the respondents did not attempt to provide an age or said they did not know, while 20.5% of the responses were classified as "always existed/ infinite/not applicable" (corresponding approximately to the 26.4% who responded to the first question segment that the Universe has always existed).

The third part of this question asked how we know the age of the Universe (Figure 8). Although more than a fifth (21.3%) of the participants did not know or left the question blank, nearly another fifth said that it is

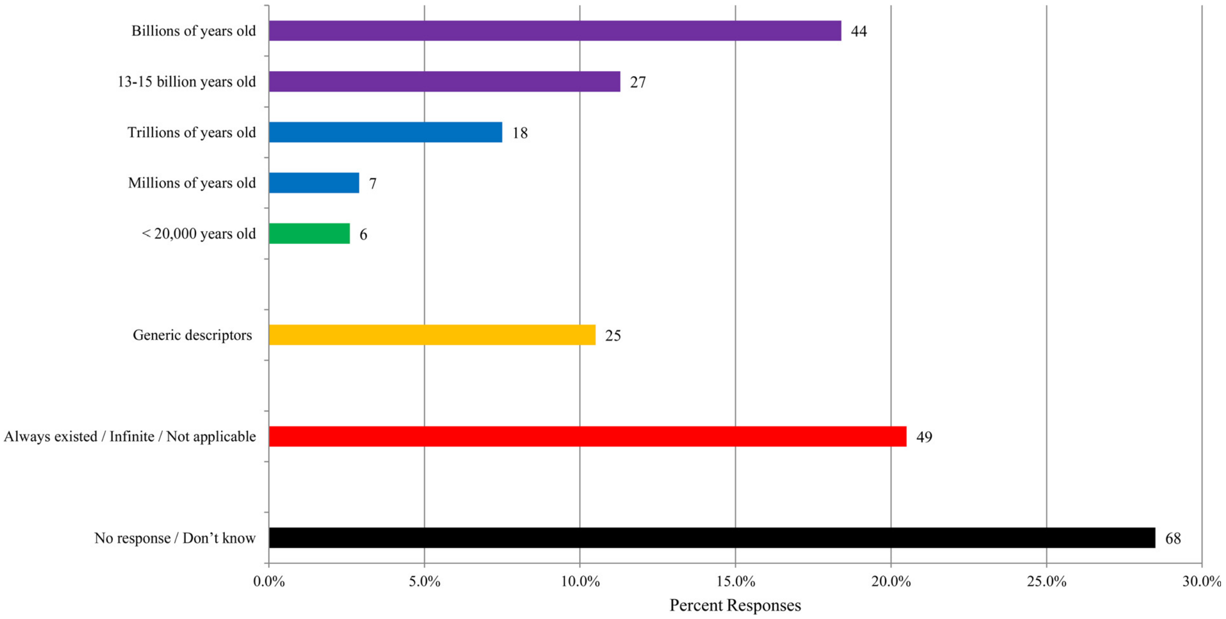


Figure 7. Themes from questions on the age of the Universe ($N = 239$). Labels to the right of each bar indicate the number of responses within the given category.

not possible to know this (17.6%). Additionally, 12.6% of the responses appealed to the perceived authority of a textbook, teacher, or other information source, with responses being comparable to the same category used in the evidence for the Big Bang section above. Of the participants who attempted to provide a scientific process or phenomenon as their answer, the largest groups said that the Big Bang marked the beginning of the Universe (11.3%) or that in order to find the age of the Universe, we must first use dating methods to find the age of objects *within* the Universe (11.7%). It is important to note here that in most cases, these were simplistic or inaccurate methods, many of which used too small a timescale (such as carbon dating of fossils).

4.4.3. Evolution of the Universe Over Time

Questions B*2 and B1 ($N = 224$) asked students to describe how, if at all, the Universe changes over time. Although a large portion of the respondents (89.8%) indicated some kind of change(s), the answers often

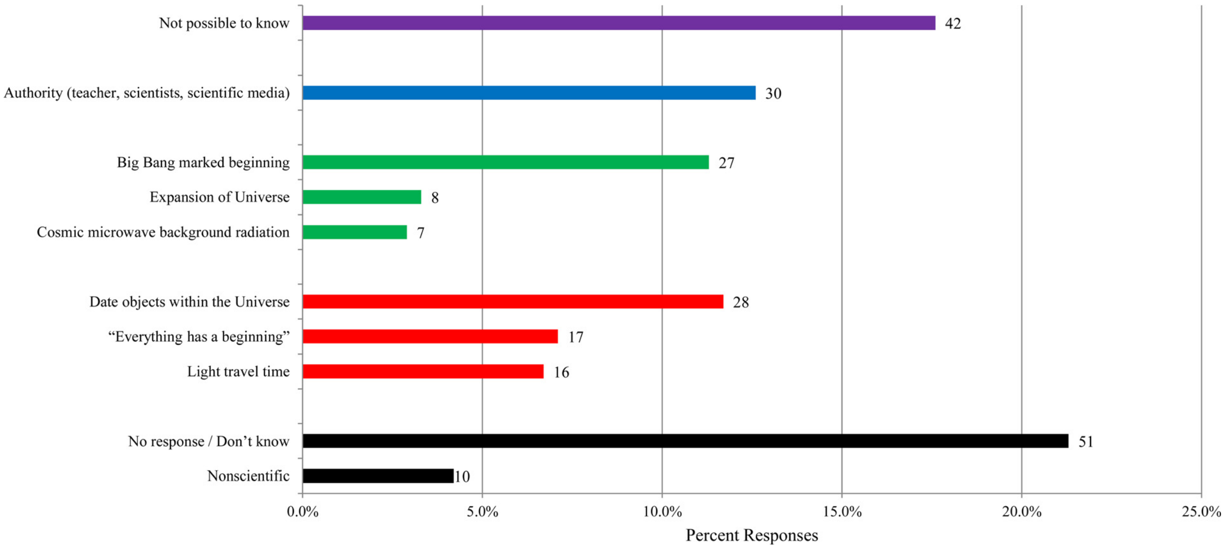


Figure 8. Themes from questions on how astronomers know the age of the Universe ($N = 239$). Labels to the right of each bar indicate the number of responses within the given category.

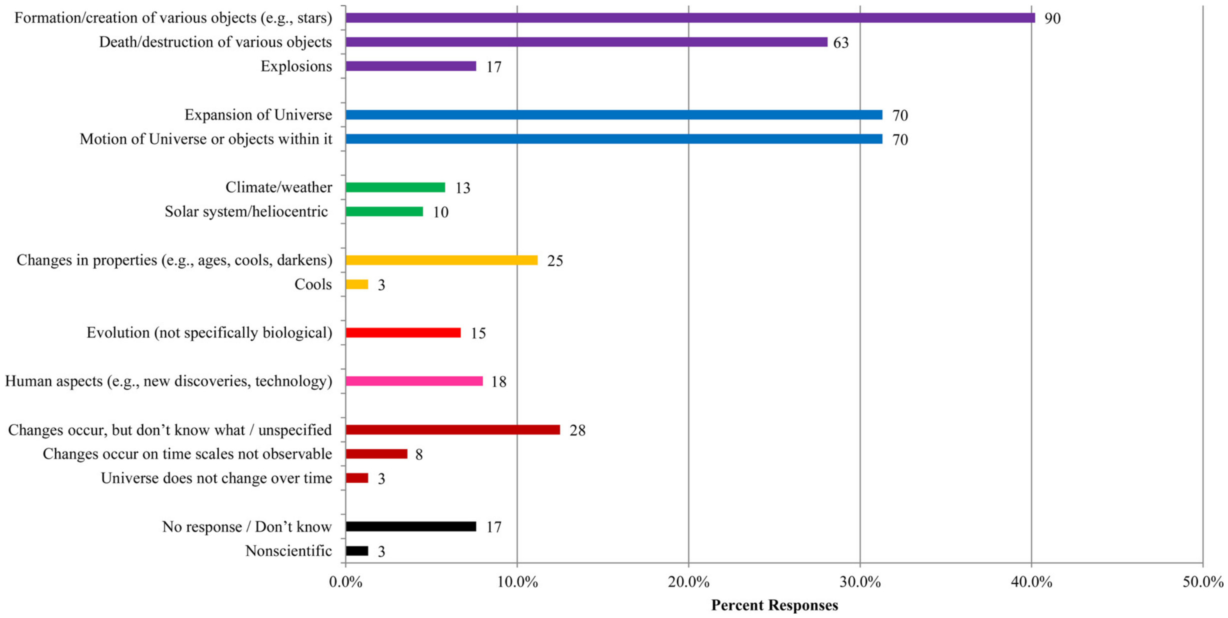


Figure 9. Themes from questions on evolution of Universe over time ($N = 224$). Labels to the right of each bar indicate the number of responses within the given category.

indicated that the students do not have a good sense of the systematic or large-scale changes over time. Instead, many of the responses focused on changes by objects within the Universe (e.g., planets and stars are created and destroyed, or move throughout the Universe). Two of the responses that we might want to see after instruction—the expansion of the Universe and that the Universe cools over time—were stated by 31.3% and only 1.3% of the participants, respectively. No student indicated changes in entropy or density. Nearly a tenth (8.0%) of the students focused not only on the Universe or its comprising objects but rather on human understanding of the Universe. The themes identified in these questions are further described in Figure 9.

5. DISCUSSION

It should come as no surprise that students are more willing to express their understanding about topics with which they are more familiar, even if those ideas are inconsistent with scientific knowledge. The response rate on the questions regarding definitions of the Solar System, Galaxy, and Universe, for example, was 90.5%. In contrast, for topics that are less recognizable, fewer students even attempt a response, instead leaving the question blank or stating outright that they do not know. The clearest example of this is the definition of dark energy (29.0% no response, 12.9% do not know), a concept that astronomers struggle to convey to the public in a meaningful way. Additionally, although a formal analysis on this aspect was not performed, it appeared that students with prior astronomy coursework were more likely to provide longer, more detailed responses.

A number of our questions lead us to conclude that students have difficulty with definitions of terms, especially when those terms may be confused by everyday language. In the case of the light-year, for example, a large portion of students mistakenly believes this term to be a measure of time. While it is certainly *related to* time, it is not *itself* a time measurement. Thus, by using a term that contains reference to a time unit (i.e., year), we may expect such confusion to continue. The image of the Big Bang as an explosion, held by a large proportion of students (50%; see also Prather, Slater, and Offerdahl 2002; Wallace, Prather, and Duncan 2012), is another case where the vernacular may be influencing students' ideas. Previous research within astronomy (Bailey *et al.* 2009), and in other disciplines such as physics (Jewett 2008; Prather 2005; Williams 1999) indicate this is a common problem. With the data collected in this study, we are not able to determine whether these problems result from students trying to define on-the-spot a term with which they are unfamiliar or whether they have learned the term in the past but cannot remember it correctly. It is worth noting, however, that the definitions provided by students who indicated they had a prior astronomy course were not always correct, suggesting that there may be, in some cases, more at play than just a lack of opportunity to learn.

In questions for which there was some overlap of content with previous research, we generally saw agreement between our sample and those studies. Students' responses about the Big Bang tend to be consistent with work by Prather, Slater, and Offerdahl (2002) and Wallace, Prather, and Duncan (2012), although the percentages vary somewhat. The results from questions relating to the composition of the Universe—specifically relating to the formation of chemical elements—are consistent with responses on this topic in research on stars (Bailey *et al*. 2009).

Finally, we see that many students do not understand the nature of scientific evidence or how it is possible to answer questions about the nature and history of the Universe. With nearly a fifth of our participants believing that it is *not possible* to know the age of the Universe, for example, we surmise that students may not have had adequate experience with thinking through the process of how scientists draw their conclusions, focusing instead on only the conclusions themselves. There is an opportunity for cosmologists in particular to help communicate what they do in order for students and the public to understand the processes of science.

6. IMPLICATIONS, CONCLUSIONS, AND FUTURE DIRECTIONS

One of the important implications of our research is for instructors, curriculum developers, and textbook authors to be cognizant of and responsive to the challenges that students face when learning the language of science, in particular, when there is room for confusion with everyday language or more general uses of a term. By maintaining careful consistency, and deliberately pointing out relevant differences, we may be able to help clarify these ideas for students.

In our own ongoing curriculum development (Coble *et al*., in press), it is critical that we build upon students' existing ideas about the topics at hand. The present research study, along with our companion pieces (Coble *et al*.; Trouille *et al*.) and previous research (e.g., Prather, Slater, and Offerdahl 2002; Wallace, Prather, and Duncan 2012), allows us to create carefully designed instructional sequences that take this prior knowledge into account (Bransford, Brown, and Cocking 1999; Donovan and Bransford 2005). As just one example, preinstructional ideas such as those uncovered here inform the creation of "starter questions," in which students read a scenario of common statements made by students and write explanations of why they agree with or disagree with the statements (a form also used within other materials such as *Lecture-Tutorials*; Prather *et al*. 2007). A more detailed description of this process is beyond the scope of this article, but see also Coble *et al*. (2012).

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. By building upon these ideas, we can help students move toward improved understanding of both the processes and outcomes of cosmology and science more generally. Future research will include an investigation of students' ideas about the shape and fate of the Universe and gravitational forces in nongeocentric and non-Newtonian contexts.

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Appendix

Table A1. Definitions of terms from recent textbooks

Term	Bennett *et al.* (2010)	Chaisson and McMillan (2010)	Slater and Freedman (2012)
Light-Year (ly)	The distance that light can travel in 1 year, which is 9.46×10^{12} km. (p. G-8)	The distance that light, moving at a constant speed of 300 000 km/s, travels in 1 year. One light-year is about 10×10^{12} km. (p. G-9)	The distance light travels in a vacuum in 1 year. (p. G-4)
Solar System	(*or star system*) A star (sometimes more than one star) and all the objects that orbit it. (p. G-13)	The Sun and all the bodies that orbit it, Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, their moons, the asteroids, the Kuiper belt, and the comets. (p. G-14)	*Not included in glossary. From text:* The star we call the Sun and all the celestial bodies that orbit the Sun—including Earth, the other seven planets, all their various moons, and smaller bodies such as asteroids and comets—make up the solar system. (p. 3)
Galaxy	A huge collection of anywhere from a few hundred millions to more than a trillion stars, all bound together by gravity. (p. G-5)	Gravitationally bound collection of a large number of stars. The Sun is a star in the Milky Way Galaxy. (p. G-6)	*A large assemblage of stars, nebulae, and interstellar gas and dust. (p. G-3)*
Universe	The sum total of all matter and energy. (p. G-15)	The totality of all space, time, matter, and energy. (p. G-16)	*Not explicitly defined in glossary or text.*
Dark matter	Matter that we infer to exist from its gravitational effects but from which we have not detected any light; dark matter apparently dominates the total mass of the Universe. (p. G-3)	Term used to describe the mass in galaxies and clusters whose existence we infer from rotation curves and other techniques, but that has not been confirmed by observations at any electromagnetic wavelength. (p. G-4)	*Nonluminous matter that is the dominant form of matter in galaxies and throughout the Universe. (p. G-2)*

Table A1. (*Continued.*)

Term	**Bennett *et al.* (2010)**	**Chaisson and McMillan (2010)**	**Slater and Freedman (2012)**
Dark energy	Name sometimes given to energy that could be causing the expansion of the Universe to accelerate. *See* cosmological constant. (p. G-3) *Also*, *cosmological constant:* The name given to a term in Einstein's equations of general relativity. If it is not zero, then it represents a repulsive force or a type of energy (sometimes called *dark energy* or *quintessence*) that might cause the expansion of the Universe to accelerate with time. (p. G-3)	Generic name given to the unknown cosmic force field thought to be responsible for the observed acceleration of the Hubble expansion. (p. G-4)	A form of energy that appears to pervade the Universe and causes the expansion of the Universe to accelerate but has no discernible gravitational effect. (p. G-2)
Big Bang	The name given to the event thought to mark the birth of the Universe. (p. G-2) *Also*, *Big Bang theory*: The scientific theory of the Universe's earliest moments, stating that all the matters in our observable Universe came into being at a single moment in time as an extremely hot, dense mixture of subatomic particles and radiation. (p. G-2)	Event that cosmologists consider the beginning of the Universe, in which all matters and radiation in the entire Universe came into being. (p. G-2)	If we look far enough into the very distant past, there must have been a time when the density of matter (in the Universe) was almost inconceivably high. This leads us to conclude that some sort of tremendous event caused ultradense matter to begin the expansion that continues to the present day. This event, which we have named the **Big Bang**, marks the creation of the Universe. (p. 377)

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