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Astronomy Education Review

2013, AER, 12(1), 010111, http://dx.doi.org/10.3847/AER2012039

Investigating Student Ideas about Cosmology II: Composition of the Universe

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Received: 09/6/12, Accepted: 06/26/13, Published: 08/20/13

Abstract

Continuing our work from a previous study (Coble *et al*. 2013), we examine undergraduates' ideas on the composition of the Universe as they progress through a general education astronomy integrated lecture and laboratory course with a focus on active learning. The study was conducted over five semesters at an urban minority-serving institution. The data collected include individual interviews ($N = 15$) and course artifacts ($N \sim 60$), such as prelab surveys, and midterm and final exam questions in a variety of formats. We find that students easily obtain a superficial knowledge of the origins of the chemical elements and the existence of dark matter and dark energy, which they are generally unaware of pre-instruction. However, they are hindered in their ability to reproduce the argument for the existence of dark matter at least in part because of weaknesses in their graph-reading abilities.

1. INTRODUCTION

1.1. Background and Motivation

Despite rapidly advancing our current understanding of the Universe, the vast gains in cosmological science have had limited impact on education. Understanding the underpinnings of the Universe can deepen students' sense of wonder and help them appreciate their origins, in the broadest sense. Cosmology also provides a powerful means to help students understand the link between a scientific worldview and the data upon which it is based. Thus, it is important to create bridges between new scientific knowledge and the astronomy classroom.

Both broad scale science education reform efforts (American Association for the Advancement of Science [AAAS] 1990, 1993; Bransford, Brown, and Cocking 1999; Fox and Hackerman 2003; National Research Council [NRC] 1996, 2003, 2012) and some members of the astronomy education community (e.g., Pasachoff 2002) call for an increased inclusion of modern topics and current research results in K-16 curriculum. Helping students understand the knowledge gains made through cosmological research is one way we can address such demands.

One such area in which a great deal of current cosmological research is taking place is the composition of the universe. To understand this topic, students should know what the Universe is made of, where that "stuff" came from, and how we (humans) fit into that picture. Like many areas of cosmology, these fundamental questions have been pondered throughout human history and are at the core of our sense-of-self. The answers are also of vital interest to the scientific community. Cosmological observations have revealed that the overall composition of the Universe is 4% atoms, 23% dark matter, and 73% dark energy (Spergel *et al.* 2003; see Planck Collaboration 2013a,b for results since the present study was conducted). Dark matter is matter that does not emit light or other electromagnetic radiation; thus, its presence is inferred from gravitational effects on matter that can be seen or from the gravitational lensing of background radiation. Dark matter makes up more than 80% of matter in the Universe (Massey *et al.* 2007). Similarly, dark energy is quantified by its interactions with other objects. Dark energy comes from a yet-to-be-determined form of matter or property of space that is causing the accelerating expansion of the Universe (Perlmutter *et al.* 1998; Riess *et al.* 1998).

Dark matter and dark energy are important for students to understand for several additional reasons. First, together they comprise more than 95% of the matter-energy budget for the Universe; most of the Universe is not made of the same "stuff" as us. The existence of dark matter and dark energy has been inferred only through astronomical observations. The notion that the vast majority of the material of our Universe could be composed of something of which we have been entirely ignorant for essentially all of history is a compelling one and can be highly motivating for students. Second, the investigations and debates on dark matter and dark energy help put the process of science into its human context, something that is often lacking in traditional science instruction. These debates do, however, capture the attention of the popular media. For example, recent results from the European Space Agency's Planck satellite reported in *The New York Times*' science section garnered more than 340 comments in three days on the online version (Overbye 2013). Finally, the study of dark matter and dark energy will allow the students to put their understanding of gravity and motion to work, a theme in many ASTRO 101 courses, and see how these ideas from physics apply to a diverse range of subjects.

We know from previous studies (e.g., Deming and Hufnagel 2001) that most beginning astronomy undergraduate (a.k.a. ASTRO 101) students have never had an astronomy course of *any* kind; additionally, most ASTRO 101 students will not take any further science classes (Rudolph *et al.* 2010). These students' prior understanding of the Universe— especially as it relates to cosmological topics—has been formed through exposure in the media (news, television, and movies) or in their limited astronomy experiences in K-12 education. Whatever understanding they gain from ASTRO 101 will have to serve them as they take their places as adult citizens, and perhaps even as teachers. Providing ASTRO 101 courses that are based on a modern view of the universe and a treatment of science that includes students working with real astronomical data to construct their understanding can thus contribute to the development of a more scientifically literate society. In fact, such a course may be our only opportunity to help students add to their understanding or overcome alternative conceptions about cosmology.

A variety of literature has shown that alternative conceptions of science content—i.e., ideas that differ from the accepted scientific viewpoint—exist across all topics, grade levels, and student backgrounds (see, e.g., Duit 2006 and references therein). Determining the range and frequency of these "alternative conceptions" is an important first step to improving instructional effectiveness in cosmology, and astronomy education researchers are beginning to document them. In the case of cosmology topics, Prather, Slater, and Offerdahl (2002) examined middle school, high school, and college students' ideas about the Big Bang. A subsequent study by Wallace, Prather, and Duncan (2012) included other cosmological topics, such as the argument for the existence of dark matter. Alternative conceptions in other astronomy topics are discussed in reviews by Bailey and Slater (2003) and Lelliott and Rollnick (2010). It is with this background in mind that we developed our current research project.

1.2. The Present Study

Our group is attempting to bridge the new results in cosmology research to instruction through two projects: conducting research on undergraduate learning in cosmology and developing a series of web-based cosmology learning modules for general education undergraduate students (Coble *et al.* 2012; Coble *et al.*, in preparation). Both the research and our curriculum development are organized around three major cosmological themes: (1) structure—the vast distances, timescales, and hierarchical nature that constitute the organization of the Universe; (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 model and the age and expansion of the Universe. The inclusion of how this knowledge is supported by observational and experimental evidence and why these processes occur (according to the laws of physics) is also integral to our approach to this large-scale project.

The present paper is one in a series examining the nature and frequency of students' ideas about structure, composition, and change. Our intent is to catalog thoroughly students' ideas, from a single institution, using multiple data sources. We are particularly interested in documenting the range of student ideas as sampled over the course of the semester, not limiting our investigation to students' pre-instruction ideas as other studies have done. A mixed-methods approach, including both qualitative and quantitative data sources, allows us to create a bigger picture and derive a deeper understanding of students' ideas. The use of 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 II), we examine student ideas on the composition of the Universe. A similar methodology is described in Coble *et al.* (2013, Paper I), in which we explored student ideas on distance and structure. In Trouille *et al.* (2013), we investigate student ideas on the Big Bang Theory and the age, expansion, and history of the Universe. Previously, Bailey *et al.* (2012) presented the results of a nationwide, open-response, pre-instruction survey on various cosmological topics, including those discussed in Papers I-III and more. A future analysis will look at data associated with students' ideas on the geometry, accelerating expansion, and fate of our Universe.

Section 2 describes our methods, including the setting, participants, data sources, and analysis procedure. We then discuss students' ideas on the chemical elements, dark matter, dark energy, and overall composition in Sections 3–6, respectively. 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

Over five semesters (Fall 2008, Spring 2009, Spring 2010, Fall 2010, and Spring 2011), multiple sources of data were collected from the general education astronomy course at Chicago State University (CSU), an urban, minority-serving institution. The demographics of the students in the astronomy 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 laboratory class, with approximately 15 students per semester. The class meets four hours per week for 15 weeks. It covers the major topics typically taught in an ASTRO 101 course (Slater *et al.* 2001), with somewhat more of an emphasis on cosmological topics than is typical at other institutions. Coble taught the course all semesters except Spring 2011, during which Trouille taught the course using Coble's curricular materials.

As guiding principles for the class, we want students to learn both the content and processes of science, including making predictions and testing them experimentally, asking questions in order to gain understanding, relating science to everyday life, and reflecting on results; the class forms a scientific community. Ours is an active classroom; interactive lectures are integrated with short and long tasks, such as CSU-developed worksheets, *Lecture-Tutorials* (Adams *et al.* 2005) (Note-1), activities from *Mastering Astronomy* (Note-2), and longer laboratory-oriented activities. Laboratory activities were adapted from existing verification-style (or "cookbook") laboratories following the guiding principles for our course materials. Students also complete an observing project using the Global Telescope Network (Note-3). A CSU-developed course workbook ties materials together. We will provide more details on the activities relevant to specific cosmological topics as students' 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.

Table 2.1. Relative schedule of topics, cosmology-related laboratory activities, and data collection points. The schedule was the same for all five semesters of data collection. Interviews (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 ($N = 74$) for pretest	HW #1 due ($N = 55$)
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 ($N = 47$) for pretest	Interview: C
Measuring Distances	Lab #9: Measuring Distances ($N = 36$) for pretest	Lab #8 due Interviews: D, E
Expansion and Age of the Universe	Lab #10: Hubble Law	Lab # 9 due Interview: F
Big Bang, 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 #2 do not relate to cosmology topics and so are not listed here.

[b] Assessments were given before the weeks' topics were covered in class.

[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.

2.2. Data Collection

The dataset for the project consists of pre-course homework essays ($N = 55$), laboratory pretests ($N \sim 60$), and exam responses ($N \sim 60$), as well as in-depth interviews ($N = 15$). 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 or was present in class for all prelab surveys, and there was some attrition over the course of each semester. The number of responses for each question is presented in the appropriate data tables in each section. Course artifacts were collected over five semesters and interview data were collected over the final four semesters. Each of these is described further below.

Each semester during the first week of class, students were assigned to write a 2-3-page homework essay describing the Universe as they currently understood it. Students were urged to describe what they really thought and were graded on completeness only, not the correctness of their descriptions. Students were asked to address their ideas and beliefs about three themes: (1) the physical size and structure of the Universe, (2) how the Universe changes over time, and (3) how humans fit into the big picture. We provided guiding questions for each theme, but students were not required to respond to every question.

Other class data included prelab surveys, or "pretests," and midterm and final exams. Laboratory pretests were open-ended written response format, administered after lecture but before laboratory. Exam questions included long-format open-response (essay) questions and short-format questions such as matching and ranking questions, multiple-choice (MC), true-false (T/F), and fill-in-the-blank (FIB). Short-format exam questions were 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. Midterm Exams 1 and 3 were relevant to the larger project, but only questions from Exam 3 are analyzed in this paper.

The interviews were semi-structured, lasted approximately 30–40 min each and were audio-recorded and 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) precourse surveys. However, all interviewees were not asked all of the main questions. The purpose of a semistructured 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). Interviews took place throughout the latter half of each of four semesters (near the time when most cosmological topics were being covered in depth). Thus, we are able to examine student ideas throughout the process of learning cosmology. We use quotes and themes from the interviews as illustrative examples of the student ideas we gathered through our other course artifacts. It should be noted that for this paper, interviews take on slightly greater emphasis than they did in Papers I and III because of a reduced data set as described in Section 3. Results from a small number of interviews should, of course, be interpreted with some caution. Tables and figures note the number of interviewees who were asked each question.

2.2.1. A Note About Pre-course Homework Essays

The nature of the precourse homework essay allowed students to choose the pathway of expressing their understanding of astronomy topics at that time. Although these essays were part of our larger data set, it turns out that no responses are relevant to this paper's focus on the composition of the Universe. For example, of the 55 students who submitted precourse homework essays, none described chemical elements or their origins. Furthermore, despite coverage in popular media, none of the essays discussed dark matter or dark energy. Students were not specifically asked to discuss these topics, and so the lack of discussion does not necessarily imply a lack of knowledge or understanding. It is telling, however, that no student discussed dark energy in response to the guiding question, "Do objects in the Universe move around, and if so, how?" and no student mentioned dark matter in describing the important components to the Universe. Because of the lack of discussion on these topics, precourse homework essays will not be discussed in the results Sections 3–6.

2.3. Data Analysis Procedure

We used a mixed-methods approach in analyzing the data. For the laboratory pretests, exam essay questions, and interviews, we carried out an iterative process of coding to generate a comprehensive list of recurring themes. We then identified the fraction of students who discussed a given theme in their response. Open-response essays from the pretests and exams were also coded for degree of completeness and correctness, by comparing the actual response to the desired response (which may contain more than one element). Table 2.2 describes the rubric for this analysis. Correct answers are provided with the questions in the relevant data analysis tables in the Appendix.

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-4) (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 can be 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

Table 2.2. Coding scheme for open-response prelab and post-test essay questions

Code	Meaning	Description
C	Correct	the response was complete and contained no wrong statements
I	Incomplete	the response was missing one or more of the identified elements required for a correct answer
P	Partial	the response contained both incorrect and correct elements
W	Wrong	no element of the response matched the identified elements of a correct answer
T	True but irrelevant	included statements that were true but did not address the question in any meaningful way
NS	Non-scientific	non-scientific response
NR	No Response	no response

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. 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 used the same conservative significance level of 0.1 to determine whether the two semesters' results could be aggregated. In every case for the present topics, the p-value was greater than 0.1 (range 0.1–0.92), so we felt comfortable aggregating results across semesters.

In order to avoid disrupting the flow of the analysis, we provide summary tables of the aggregated data in the main body of the paper below. In corresponding tables in the Appendix, we provide the full text of the questions asked, the expected correct answers used for coding, and detailed results for each item, broken down by semester, as well as the KW H-statistic and p-value or the KS-statistic and the p-value as appropriate.

In each section below, we present the results approximately chronologically: laboratory pretests where applicable, interviews, and exams. This creates a coherent narrative of students' 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. Some description of the curriculum is given as context for the environment in which the development of student ideas is taking place, however it is not our intention to provide detail in this regard or to measure the effectiveness of the curriculum.

3. CHEMICAL ELEMENTS

In the CSU class, students learn about the composition of atoms and where they come from through lectures and homework. Students trace the history of chemical elements, and in doing so learn that the hydrogen in their bodies was created in the first few minutes of the Universe's existence by Big Bang nucleosynthesis (BBN). They further learn that heavy elements—such as the carbon, oxygen, and iron in their blood—were created by fusion in the cores of stars, and that the gold in their jewelry came from supernova explosions. By providing examples in a way that is relevant to the students' immediate lives, they can see how humans are directly connected to the Universe.

3.1. Results

The assessment of student understanding of the origins of elements came from select interviews and exam questions. There were no laboratory pretest questions associated with these topics. Results from the interviews and exam questions are described below.

A subset of the students interviewed was asked how the chemical elements formed (Figure 3.1). The results in the figure are split according to when in the semester the interviews occurred. Two students were interviewed prior to in-depth instruction on stellar nucleosynthesis, stellar evolution, and BBN; three students were

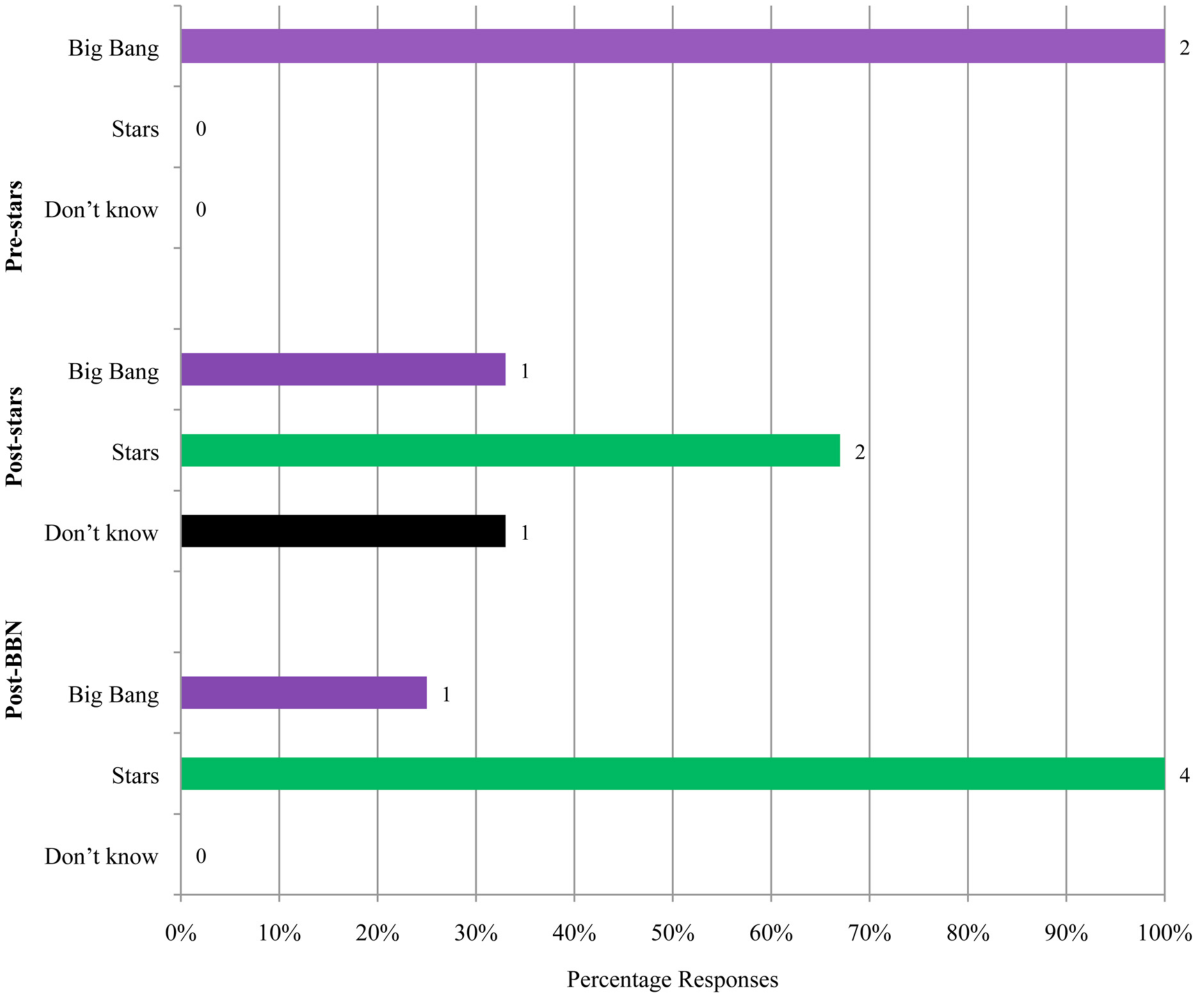


Figure 3.1. Interviews: Origins of the chemical elements, theme frequencies. All students were briefly introduced to the history of the Universe (including BBN) in the first few weeks of class. Detailed instruction breaks down as follows: prestars: $N = 2$, poststars (but pre-BBN): $N = 3$, post-BBN (and poststars): $N = 4$.

interviewed after in-depth instruction in the stellar origins of the elements but prior to in-depth instruction on BBN; and four students were interviewed after in-depth instruction on both the stellar origins of the elements and BBN. All students had been briefly introduced to the history of the Universe (including BBN) during the first few weeks of class. Across all of these interviews, only one student was completely unaware of the origins of the elements. In all cases, the themes that arose were that chemical elements were formed during the Big Bang or in stars, or the student did not know.

We probed student postinstruction understanding of the origins of the chemical elements using an open-ended essay question on the Final Exam ($N = 58$, Tables 3.1, A3.1). Table A3.1 lists the specific question and the ideal correct answer that was used for rubric coding (recall Table 2.2). Student responses were only Correct about a quarter (24%) of the time, whereas more responses were Incomplete (33%) or Partial (29%). Few students were Wrong (9%) and few students did not respond to the question (5%).

Responses to this question were further coded for themes (Figure 3.2) to determine *what* students were saying (rather than the previous coding that focused on the alignment of responses to the ideal answer). Nearly half (47%) of students answered that elements formed in the Big Bang/first few minutes of the Universe and half (50%)

Table 3.1. Final Exam: Origin of chemical elements (Essay)

N	C	I	P	W	T	NS	NR
58	**24%**	33%	29%	9%	0%	0%	5%

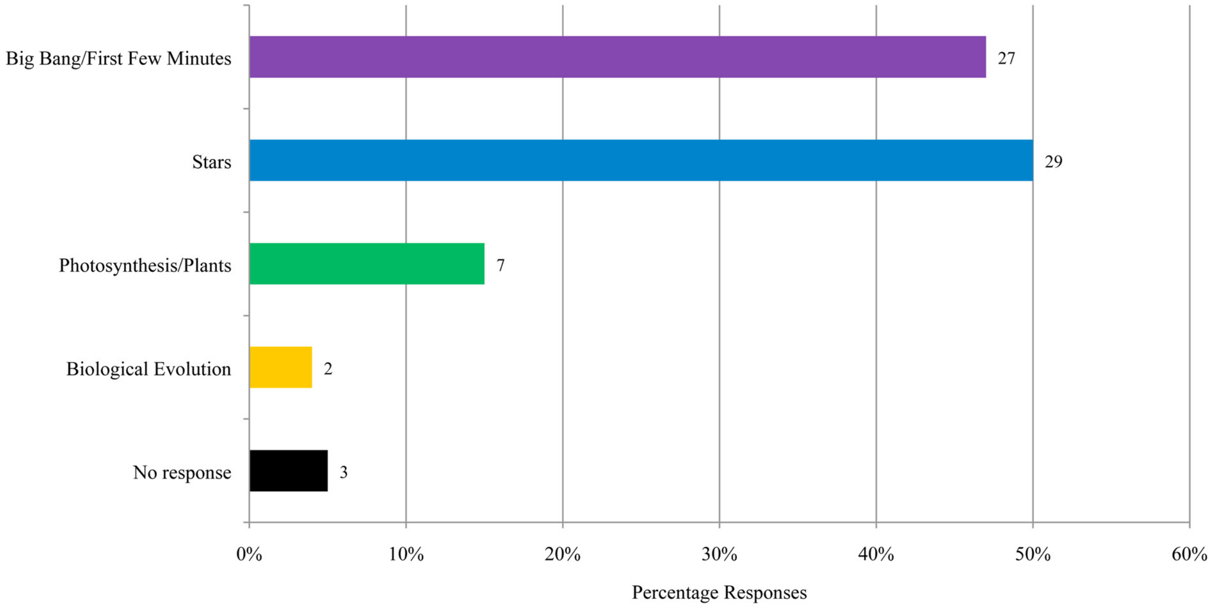


Figure 3.2. Final Exam: Essay question on composition, theme frequencies. $N = 58$ essays were collected. However, a correct answer includes several themes, so the percentages add up to more than 100%. Students were asked to discuss the origins of several chemical elements, including: hydrogen, oxygen, carbon, and iron.

responded that elements formed in stars/stellar evolution. Two Earth-based themes were also noted: 15% responded that oxygen on Earth came from photosynthesis/plants while 4% mentioned biological evolution. Photosynthesis as the source of oxygen in Earth's atmosphere was only briefly discussed in class. Biological evolution is not a correct response to this question. In many cases, students did not specify which elements were created in any given process, so it is not possible for us to determine the accuracy of their understanding of this aspect. Because students were asked to describe how several types of elements formed, these numbers add up to greater than 100%.

3.2. Implications

Our exams probe students' post-instruction ideas about origins of the chemical elements while interviews probe students' ideas throughout the semester. Students do not always give a fully correct and detailed response to where the chemical elements came from, but the majority of them have at least some idea post-instruction (100% Correct/Incomplete in interviews conducted after in-depth instruction in stellar evolution and BBN and 86% Correct/Incomplete/Partial on exam essays).

In pre-course open-ended surveys, Bailey *et al*. (2012) found that students come to an ASTRO 101 class generally unaware of where chemical elements came from. In that study, more than half (53%) of the participants who were asked where the chemical elements were formed said they did not know or did not respond. Our data suggest that students can learn about the origins of elements through instruction and respond at high levels. The specific responses students provide do depend upon what instruction has taken place, as evidenced by the themes noted in Figure 3.1, although this should not come as a surprise.

Although this is a topic that could be connected to secondary education where a large focus is on understanding the nature of chemical elements, it appears that this is not likely being addressed. Making such connections explicit in earlier instruction might provide an entry point for helping students understand the relationship between humans (and the elements that are critical for life on Earth) and the larger Universe. When such a connection is not being made prior to an ASTRO 101 course, instructors can also help students construct this understanding by showing how previously-learned chemistry concepts relate to astronomy.

4. DARK MATTER

After a lecture on dark matter, students complete Lab 8: *Measuring the Mass of Spiral Galaxies*. The first part of the laboratory uses the *Mastering Astronomy* tutorial on dark matter to help students gain a conceptual understanding of rotation curves (i.e., graphs of a galaxy's rotational velocity versus radial distance). In the second part of the laboratory, students measure the amount of dark matter in a spiral galaxy from its rotation curve and plot of luminosity versus radius. This part is adapted from the University of Washington's dark matter laboratory (Stinson n.d.). It was modified to shift the focus from a verification-style laboratory to one in which students predict what they will observe and then test their predictions with the data. Students focus on understanding the concepts while making measurements similar to those by Rubin and Ford (1970).

4.1. Results

We were able to first probe students' ideas using the pretest for Lab 8: *Mass of Galaxies*, which focuses on the rotation curves of spiral galaxies. Students were first shown a sketch of a rotation curve with points marked in the center, middle, and outer parts of the galaxy. Parts (a) and (b), which asked students to describe and rank, respectively, the speeds of stars at points on the curve, primarily probed students' graph-reading capabilities (Tables 4.1, A4.1, 4.2, A4.2, $N = 47$). In part (a), when students described in words the motions of stars at the centers of galaxies versus the outer parts of galaxies, their responses were Correct a little less than half (45%) of the time, and Wrong a little more than a quarter (28%) of the time. In part (b), when students ranked the speeds of stars at the center, middle, and outer parts of galaxies based on the graph, fewer responses were Correct (36%) or Wrong (11%), with more being Incomplete or Partial. A Correct response would recognize that stars near the center of the galaxy would move slowest but that those at the middle and outer parts would move at approximately the same speed ($A < B = C$). Incomplete responses often listed an order but did not indicate specific mathematical relationships between the locations, while Partials might have had the relationship between two of the locations correct but the other incorrect (e.g., $A > B = C$)

In part (c) of the pretest (Tables 4.3, A4.3, $N = 47$), students were asked to explain why rotation curves are evidence for dark matter. A complete and correct response would include that the gravitational force from visible matter is insufficient for creating the observed motion of stars, from which we infer that additional mass (dark matter) must be present but not visible. In this case, few responses were Correct (13%), while most other categories had similar or higher fractions of the responses. There were no discernible patterns to answers that were Wrong—the largest percentage—as only two students replied with approximately the same idea, whereas other responses were largely unique.

Interviews conducted after lecture and laboratory instruction provide us with some insights into some students' evolving ideas about dark matter. (Interviews conducted prior to this instruction did not include questions about dark matter.) We asked a subset of students, "What is dark matter?" (Figure 4.1, $N = 10$) and "How do we know dark matter exists?" (Figure 4.2, $N = 8$). Only one student responded that they did not know what dark matter is. Others described it as matter that cannot be seen (60%), as having a gravitational impact on its surroundings (60%), and as occupying the space between objects (30%). All students attempted to explain how we know dark

Table 4.1. Lab 8 Pretest: Reading rotation curves (part a)

N	C	I	P	W	T	NS	NR
47	**45%**	9%	15%	28%	2%	0%	2%

Table 4.2. Lab 8 Pretest: Reading rotation curves (part b)

N	C	I	P	W	T	NS	NR
47	**36%**	17%	30%	11%	0%	0%	6%

Table 4.3. Lab 8 Pretest: Dark matter and rotation curves (part c)

N	C	I	P	W	T	NS	NR
47	**13%**	23%	13%	30%	4%	0%	17%

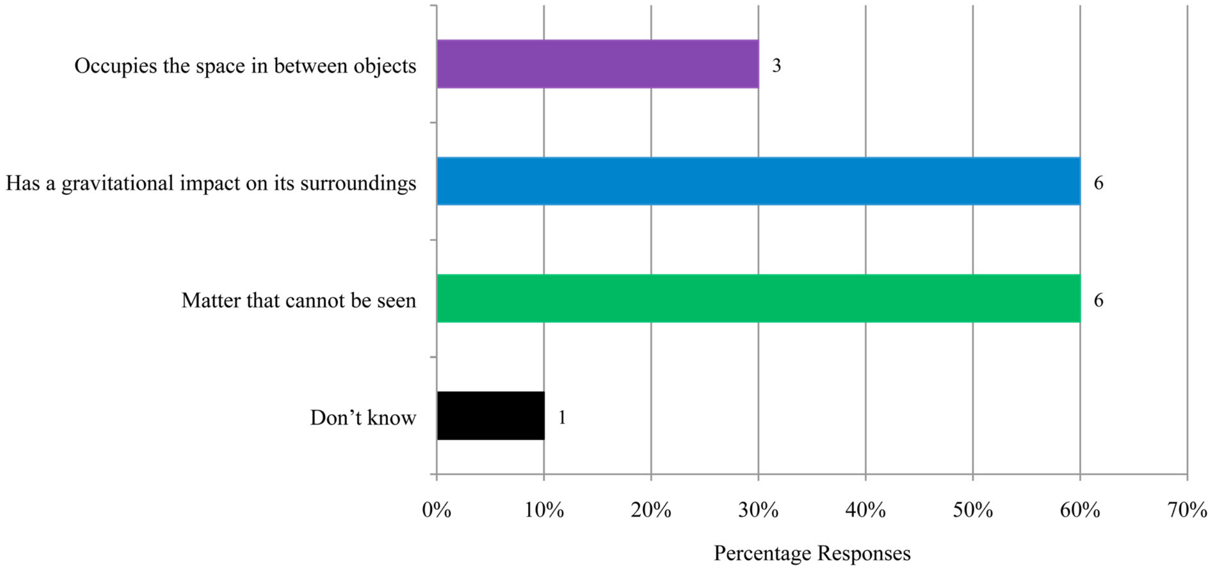


Figure 4.1. Postinstruction interviews: what is dark matter, theme frequencies. $N = 10$.

matter exists: a little more than one-third (38%) mentioned the rotation curve but did not provide the correct explanation; a little more than one-third (38%) indicated that there is evidence, but they cannot recall what it is; and one student (13%) said dark matter is detected through radio waves. Only one student was able to give a fully correct explanation for how we know dark matter exists, using a galactic rotation curve. We will revisit this issue after discussing exam results.

Two quotations from interviews demonstrate the difficulty students have fully recalling how they measured dark matter in the laboratory. As we will see below, these results are consistent with exam results.

> “*Alright, we used a uh graph, velocity and, velocity and um. Where after we did the experiment, we drew a graph and … like for example our Solar System … Oh yeah, it was velocity and distance. Where, uh for example our Solar System … as the distance increased it slowed down so I believe the graph looked like this (points to the graph) and it was a point where it became constant, well it just went straight through, I don’t know why we did that*.” – Interview H

> “*Yeah I’m trying to recall something in class and how we processed that through determining that there’s dark matter and how much matter there is. Now I can’t recall the process in which we did it but it’s a couple of steps a few steps you do in order to process that um-to-to figure out that amount in a particular part in space um within the Universe, and um I can’t seem to recall the formula we used to get that, and that’s why I’m pounding [my fist on the desk]*.” – Interview I

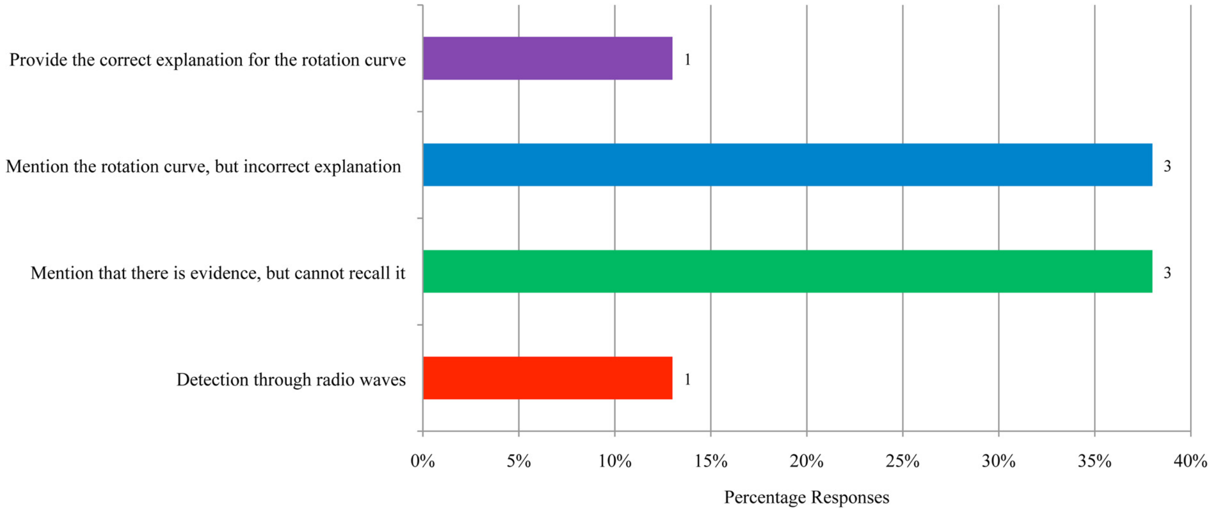


Figure 4.2. Postinstruction interviews: How we know dark matter exists, theme frequencies. $N = 8$.

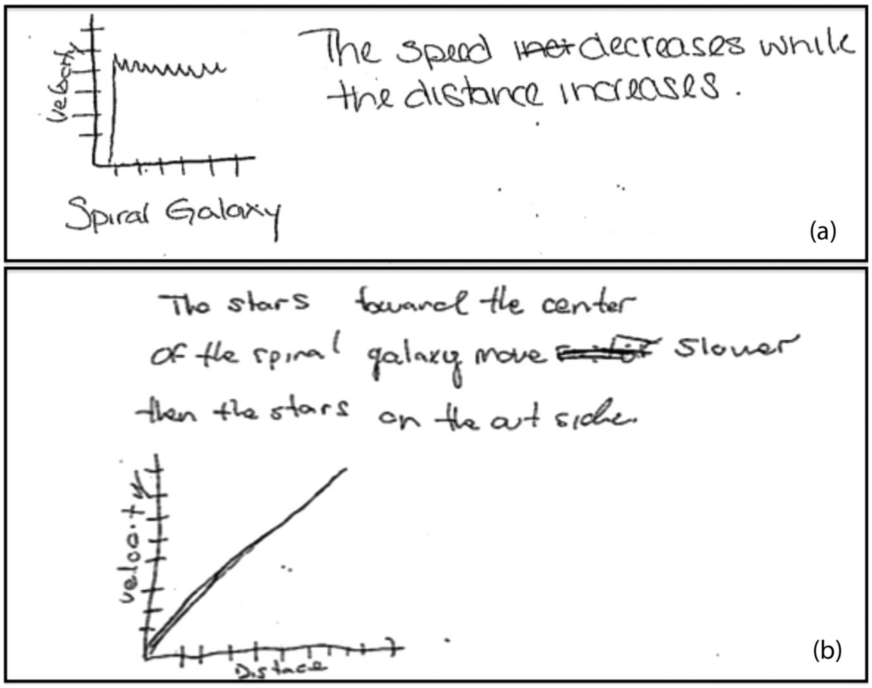
Table 4.4. Exam 3: Sketch and explain rotation curve (Essay; overall score)

N	C	I	P	W	T	NS	NR
56	**21%**	2%	54%	23%	2%	0%	0%

Exam questions addressed a number of concepts associated with dark matter. In an open-ended essay question on Exam 3, students were asked to draw a galaxy's rotation curve and describe the speeds of stars (Tables 4.4, A4.4, $N = 56$). In this case, overall responses were predominantly marked Partial (54%). This question was further analyzed by looking separately at how students drew their graphs and responded in words. In drawing their graphs, students were 36% Correct, 11% Incomplete, 7% Partial, 41% Wrong, 5% No Response. Common mistakes were drawing the wrong shape of graph (27%), missing or wrong axis labels (18%), or drawing a picture of the galaxy itself instead of its rotation curve (14%). Students fared better at explaining the motions of stars in galaxies with words than graphically: responses were coded as 50% Correct, 0% Incomplete, 13% Partial, 29% Wrong, and 7% No Response. Two examples of student responses (scored as Partial) are shown in Figure 4.3.

In Exam 3, students were also asked to explain why the rotation curves of spiral galaxies are evidence for dark matter (Tables 4.5, A4.5, $N = 56$). In this case, the largest portion of responses were scored Incomplete (45%) because students could not fully explain the steps that one would take to measure both the gravitational and luminous mass of a galaxy, as they had done in the laboratory. This was noted in the interviews as well, as illustrated by the quotations above.

We also used short exam questions to probe students' understanding of dark matter (Tables 4.6, A4.6, 4.7, A4.7). On both Exam 3 ($N = 44$) and the Final Exam ($N = 13$) we asked a T/F question about whether "dark matter is matter that we have identified from its gravitational effects but we cannot see in any wavelengths of light." On Exam 3, the vast majority (91%) of responses were Correct and on the Final Exam, more than three-quarters (77%) were Correct. We also asked a MC question on the Final Exam about what is responsible for the shape of our galaxy's rotation curve ($N = 10$). Half of the students responded correctly (Table 4.8), attributing the shape to dark matter. The most commonly selected distractor was dark energy (30%; Table A4.8). Note that although there appears to be a drop between Exam 3 and the Final Exam, the semester-by-semester results (Tables A4.6 and A4.7) show that this is a difference of only a single student and so likely not a meaningful difference.



The speed ~~that~~ decreases while the distance increases.

The stars toward the center of the spiral galaxy move ~~faster~~ slower then the stars on the out side.

Figure 4.3. Examples of partial understanding of the rotation curves of spiral galaxies. (a) This student drew the rotation curve (approximately) correctly but labeled the x-axis wrong and explained the speeds of stars according to the graph wrong. (b) This student is correct in saying that stars toward the center move slower, but did not draw the correct rotation curve for a spiral galaxy.

Table 4.5. Exam 3: Dark matter and rotation curves (Essay)

N	C	I	P	W	T	NS	NR
56	**16%**	45%	16%	18%	2%	0%	5%

Table 4.6. Exam 3: Dark matter (T/F)

N	C	W	NR
44	**91%**	7%	2%

Table 4.7. Final Exam: Dark matter (T/F)

N	C	W	NR
13	**77%**	23%	0%

Table 4.8. Final Exam: Dark matter (MC)

N	C	W	NR
10	**50%**	50%	0%

4.2. Implications

The data collected in this study do not allow us to quantify students' pre-instruction knowledge of dark matter. However, in open-response pre-course surveys, Bailey *et al*. (2012) found that students are generally unfamiliar with the term dark matter coming into an ASTRO 101 course. Our first data come from laboratory pretests, which occurred after some initial instruction about dark matter through lecture but before an in-depth laboratory activity.

When learning about dark matter from rotation curves of spiral galaxies, students might face difficulties because of weak graph reading abilities, as exemplified by our laboratory pretest data. The most common mistake is for students to think the graph shows that stars at the center of the galaxy are moving faster. This could be due to mistaking the slope of the graph for the value, or not understanding the axes. For example, one student remarked on the pretest, "The speed of star A increases, stars B and C stayed the same over time." This is not surprising given the work of other physics and astronomy education researchers who have found students' graph-reading abilities to be weak (e.g., McDermott, Rosenquist, and van Zee 1987, Trowbridge and McDermott 1980), including with respect to rotation curves (Wallace, Prather, and Duncan 2012). Some students might also assume that motions in the galaxy are similar to those in the Solar System. As one student describes on the pretest, "The speeds of stars closer to the center of a galaxy move faster than those further away. Similar to how planets move in the Solar System." Such responses were also seen by Wallace, Prather, and Duncan (2012), where an interior planet or star was most frequently selected as the fastest one, with students indicating the reason for this being its shorter path orbital path or orbital period. These difficulties could also arise from or be compounded by the unfamiliar nature of the subject.

In comparing the laboratory pretest and Exam 3 essay question on the evidence for dark matter, we see that post-instruction, there are fewer Wrong responses and instances in which students chose not to respond. At the same time, there are many more Incomplete responses from students compared to pre-instruction. There are about the same number of Correct and Partial responses pre- instruction and postinstruction. This suggests that students have learned something about dark matter, but did not master all of the learning objectives. This is consistent with interviews in which students have trouble describing the full argument and the details of the measurements that they made during the rotation curve laboratory.

During the interviews, a few students referred to dark matter as occupying the space between objects (Figure 4.1). This might be related to students' pre-instruction ideas of dark, empty spaces in the universe (Paper I); that is, students might be looking for "dark" places to put dark matter within their pre-existing mental models. Anecdotally, we have observed students in our classes pointing to places with no data in large-scale structure surveys and dark regions in large-scale structure simulations and stating that those are places in the Universe with dark matter. These students do not appear to conceive of regular matter as being embedded in dark matter as in the scientifically accepted representation. This is speculative given our current data set, but warrants further study. Buck (2013) finds that learners are better able to identify dark matter in visualizations when it is colorized using a darker color. This topic holds obvious importance for those trying to convey an understanding of dark matter and large-scale structure to undergraduates and the public at large.

Because dark matter is an important but unfamiliar topic and understanding the evidence for dark matter relies heavily on graph-reading skills (a stumbling block for many students), we suggest introducing the topic early and returning to it often. Dark matter is typically only discussed briefly in an ASTRO 101 class, but this need not be the case. It can be tied into discussions of structure, e.g., galactic halos and large-scale structure from the beginning of the course, as well as in discussions about the composition of the Universe. As we saw in Paper I, one of students' weak points in understanding galactic structure is in regard to the halo, so a discussion of how the luminous parts of galaxies are sitting in a much larger galactic dark matter halo could improve students' understanding of both structure and composition of the Universe. In addition to increasing conceptual gains, if dark matter is discussed early and often in a course, we hope it will give students a greater appreciation for dark matter's significant role in modern cosmology.

5. DARK ENERGY

Dark energy is introduced to students through lectures and homework. Already familiar with Hubble diagrams from *Lecture Tutorials* and a laboratory activity, students are shown the evidence for the accelerating Universe from supernova redshift studies. Students are briefly informed about other evidence from the concordance model as well as possible candidates for dark energy during lecture. A summary emphasizing the components of the composition of the Universe is also given via lecture.

5.1. Results

Student ideas about dark energy were first probed using interviews, although the discussion was not always in response to a direct question. During pre-instruction interviews, in response to a question about what was in the Universe, one student listed dark energy as a component of the Universe that was responsible for "forcing the galaxies apart." This student had heard of "at least one theory that eventually the dark force is going to tear everything apart, even the dark matter, even the galaxies and everything in the galaxies" (Interview G). This student watches many shows (such as PBS's "NOVA" and the History Channel's "The Universe") and reads popular books on cosmology. This led him to ask questions about the topic in class. Another student responded to direct questioning about dark energy that she did not think it had been discussed in class.

Post-instruction, we asked five students if they had heard of the term dark energy and what they thought it means (Figure 5.1). A majority of students (60%) gave a (correct) percentage describing the amount of dark energy compared to other components of the composition of the Universe; 20% of students said they remember learning about dark energy but couldn't remember anything during the interview; and 20% said, "I don't know." One student who had attributed a correct fraction of the Universe's composition to dark energy was asked a follow-up question regarding the composition of dark energy. He replied,

> "*I don't know. I don't think we know because, I don't think they know what dark matter and dark energy is. I think that's why we call it dark. Cause we [sic] in the dark.*" –Interview J

Another interview in which a student volunteered (without direct questioning) dark energy as causing the accelerating expansion of the Universe occurred postinstruction. When later asked what the dark energy is, this student replied, "I don't know."

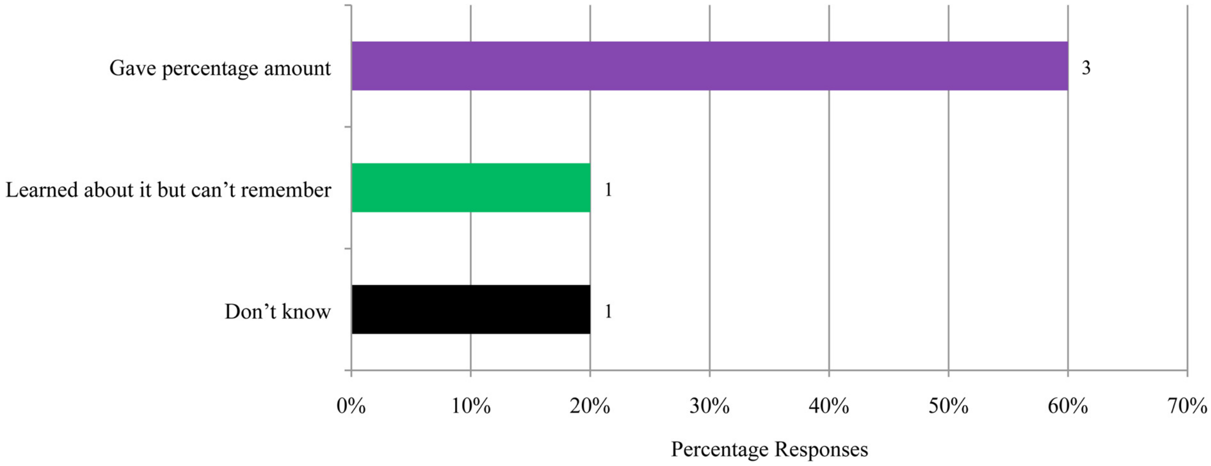


Figure 5.1. Post-instruction interviews: dark energy. $N = 5$. Students were asked if they had ever heard of the term dark energy, and what they think it means.

On a MC question on Exam 3 (Tables 5.1, A5.1, $N = 47$), a vast majority of students (81%) correctly answered that dark energy is related to the expansion of the universe. The most popular incorrect answer was that dark energy "is the energy contained in dark matter" (15%).

5.2. Implications

Like with dark matter, our data do not allow us to discuss students' pre-instruction ideas about dark energy. Bailey *et al*. (2012) found that students are generally unfamiliar with the term dark energy coming into an ASTRO 101 course, and we have no reason to expect that we would find different results. Wallace, Prather, and Duncan (2012) found that students' pre-instructional understanding of dark energy's impact on the Universe is lacking. In their study, only about 10% of students, prior to instruction, correctly identified a graph of velocity versus distance that represented an accelerating Universe. However, the authors did not make any specific connections between such questions and the presence of dark energy.

Through lecture in the CSU class, we addressed the fact that dark energy is causing the expansion of the Universe to accelerate, placed it into context with the other components of the Universe, and gave a few theoretical possibilities for what dark energy might be. The students did not engage in any active learning on these concepts. After instruction, a majority of students seem to be able to associate dark energy with the accelerating expansion of the Universe and to identify its relative abundance in the matter-energy budget of the Universe.

Given limited time and the greater availability of engaging activities to support learning about dark matter than dark energy, we decided to focus more on dark matter. Since dark energy in general was given less class time than dark matter it was accordingly given less attention in this research study. In addition to what we have presented here, we have collected related data on students' ideas on an accelerating universe and the fate of the universe, which we plan to analyze in future work.

A tantalizing result from interviews came from one student (Interview G) who watches science shows and reads popular books on cosmology; this student was particularly interested in the topic of dark energy, pre-instruction. Six other students also mentioned the influence of popular science media on their pre-instruction ideas on cosmology, but not to the same extent as the student of Interview G. This suggests an interesting line of future research investigating the role of popular science media on informing student ideas and interests in cosmology.

Table 5.1. Exam 3: Dark energy (MC)

N	C	W	NR
47	**81%**	19%	0%

We also suggest that the producers of such media could benefit from knowledge of students' ideas of cosmology, as a proxy for their general adult audiences.

6. OVERALL COMPOSITION

The discussion of chemical elements, dark matter, and dark energy is part of understanding the overall matter-energy composition of the Universe. At the time of the study, the distribution was understood to be 4% ordinary matter, 23% dark matter, and 73% dark energy (Spergel *et al.* 2003; see Planck Collaboration 2013a,b for newer results). The Universe's composition was described mainly through lecture and supported somewhat in the activities associated with dark matter (as described above).

6.1. Results

We can glean information about students' ideas on the overall matter-energy composition of the universe from interviews and exams. We asked a subset of students in interviews whether there is anything in the Universe not made of the chemical elements. Four students were interviewed prior to instruction on dark matter and dark energy and six students were interviewed postinstruction. The themes identified in the interview responses are displayed in Figure 6.1. Here there is a marked difference between pre-instruction and postinstruction ideas: all four students who were interviewed pre-instruction responded "no," whereas the majority of students post instruction gave correct answers (50% dark matter, 17% dark energy, 17% light, 33% "no").

On midterm and final exams, we asked MC questions about the overall composition of the Universe. On Exam 3, about two-thirds of students correctly identified the overall composition of the Universe (4% ordinary matter, 23% dark matter, 73% dark energy, $N = 56$; Tables 6.1, A6.1) and on the Final Exam an even greater fraction (83%) was able to do so ($N = 23$, Tables 6.2, A6.2).

On an essay question on the Final Exam (Tables 6.3, A6.3, $N = 48$), nearly half of the students (48%) were able to correctly identify something in the Universe not made of chemical elements and cite the evidence for its existence. This question was further coded for themes (Figure 6.2). The most popular responses were dark matter (67%), dark energy (19%), and black holes (8%). One or two students gave a variety of other responses each, such as subatomic particles, energy, anti-matter, DNA, and "everything is made of chemical elements."

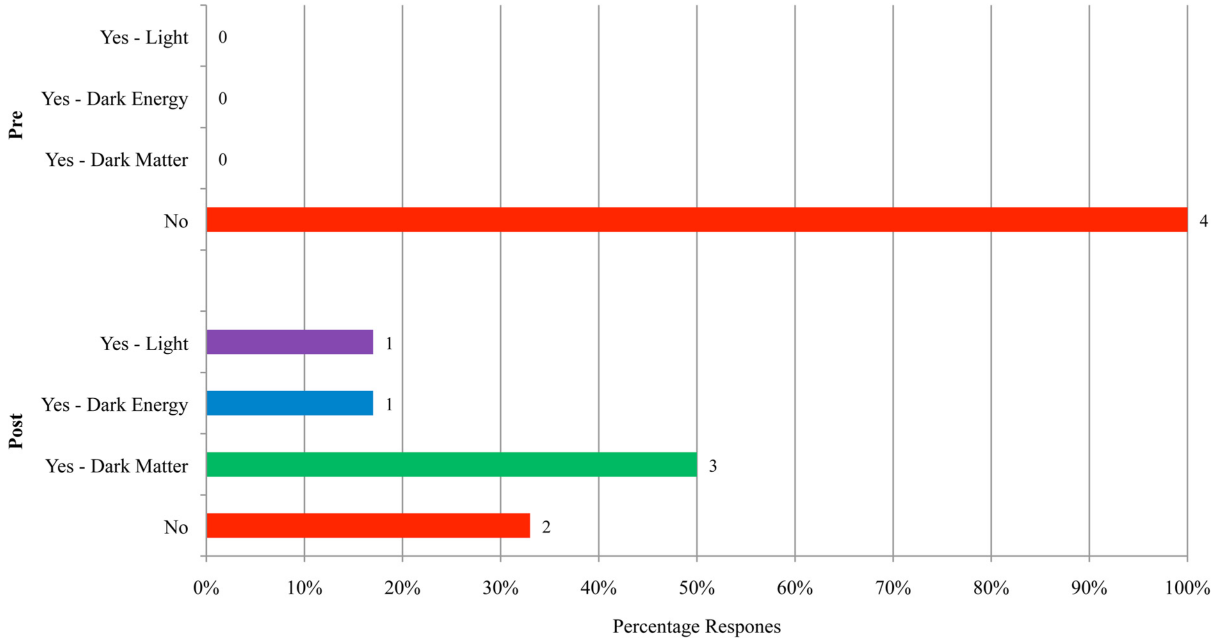


Figure 6.1. Interviews: anything in the Universe not made of chemical elements, theme frequencies. Pre: $N = 4$. Post: $N = 6$.

Table 6.1. Exam 3: Composition of the Universe (MC)

N	C	W	NR
56	**68%**	32%	0%

Table 6.2. Final Exam: Composition of the Universe (MC)

N	C	W	NR
23	**83%**	17%	0%

Table 6.3. Final Exam: Anything not made of chemical elements and the evidence for it (Essay)

N	C	I	P	W	T	NS	NR
48	**48%**	17%	15%	17%	0%	0%	4%

6.2. Implications

Four of our interviews took place prior to instruction about the composition of the Universe. All four of these students indicated they thought nothing existed that is not made of chemical elements. This seems to align with Bailey *et al.*'s (2012) pre-course open-ended surveys, which suggested that students come to an ASTRO 101 class generally unaware of components of the Universe that are not made of chemical elements. When asked whether the Universe contained anything that was not made of chemical elements, 84% of participants in that study did not know or did not respond and 9% said that everything is, in fact, made of chemical elements.

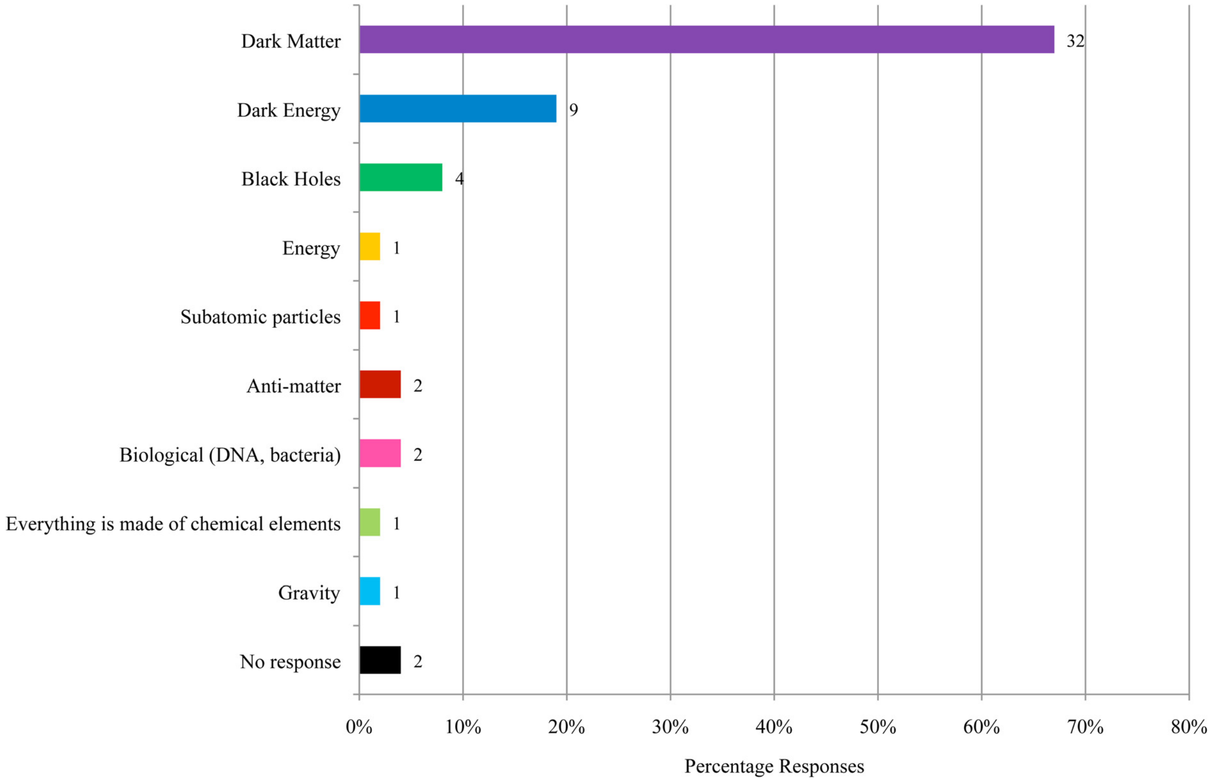


Figure 6.2. Final Exam: Essay question whether there is anything not made of chemical elements in the Universe, theme frequencies. $N = 48$ essays were collected and analyzed for themes. Students were only required to give one example, but some students listed more than one, so percentages can add up to more than 100%.

Post-instruction interviews and exam data suggest that the majority of students have at least some idea post-instruction of “stuff” in the Universe that is not made of chemical elements (80% Correct/Incomplete/Partial on exam essays, and 67% Correct in interviews). Students correctly cited dark matter, dark energy, and light as not being made of chemical elements, in both data sources. Scores for MC exam questions related to the overall composition of the Universe range between 68% and 83% Correct.

Our data seem to indicate that it is relatively easy to help students understand that the Universe is made of not just the chemical elements but also dark matter and dark energy, and how it impacts the Universe through changing the rotation curves of galaxies and accelerating the expansion of the Universe, respectively. However, this level of understanding is fairly superficial, as we have seen above. Candidates for dark matter and dark energy were discussed only briefly in the course, and so deeper understanding is unlikely at this point.

7. DISCUSSION

In this article, we have described research conducted on students’ ideas about the composition of the Universe. We used prelab surveys (“pretests”), short and long exam questions, 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. Our findings include the following:

- Students are generally unaware of dark matter when entering a course and have difficulty understanding the arguments for dark matter through observations of rotation curves of spiral galaxies.
- Likewise, students have little understanding of dark energy prior to instruction. While they can learn about how much of the Universe is believed to be dark energy and its impact (accelerated expansion), they do not yet understand possible candidates for dark energy.
- Though generally unaware pre-instruction, students can at least achieve a superficial understanding of the overall composition of the Universe. This includes the origins of the elements, as well as the presence of components that are not made of chemical elements, such as dark matter and dark energy.

In analyzing our data, we found several themes that crossed over or between the content addressed in this paper and that in Paper I and/or III.

- The topics in this paper were ones that did not earn repeated attention over the course of the semester. Accordingly, students’ understanding of these topics was not as robust as topics such as structure (Paper I).
- Students are impaired by weak math skills, including in graph reading and proportions. In the present paper, this manifests in difficulties explaining the rotation curves of spiral galaxies and the evidence for dark matter. In Paper III, we see a similar effect in students’ difficulties in recounting the measurements they used to determine the Hubble Law and the age of the Universe. In Paper I, we saw that repeated exposure to ideas such as the inverse square law and proportions allowed students to improve continuously over the semester.
- Students have difficulty visualizing dark matter halos, both in the context of galactic structure and in the context of understanding the composition of the Universe.

As a result of these findings, we offer some considerations for astronomy educators to keep in mind.

- Dark matter and dark energy continue to garner attention in popular media, and so could serve as a way of increasing students’ interest in cosmology specifically and astronomy more generally. Furthermore, that these are still open questions in astronomy without concrete answers yet can provide a way to model the processes of science to students, something that continues to be recommended by reform documents (e.g., NRC 2012).
- We recommend making connections between the composition and structure of the Universe early and often in a course, in particular by integrating dark matter halos into discussions, visualizations, and activities on galactic structure.
- There is an opportunity to help students make connections between astronomy and other content areas, especially chemistry, when discussing the composition of the Universe and the origin of ordinary matter. Many college students would have taken physical science or chemistry courses in high school and learned that we interact with ordinary matter throughout our daily lives, but these courses rarely include information about where this matter originates.

By building upon student ideas such as those presented here, we can help students move toward improved understanding of both the processes and outcomes of cosmology, and of science and mathematics more generally. The information in this series of papers is being used as the foundation for creating an innovative cosmology curriculum (Coble *et al*., in preparation) and we would encourage other authors and instructors to use this to inform their curricula as well.

Acknowledgments

This work was supported by NASA grant NNX10AC89G and by the Education and Public Outreach program for NASA's Fermi Gamma-ray Space Telescope, the Illinois Space Grant Consortium, NSF CCLI Grant No. 0632563 at Chicago State University. The authors gratefully thank Virginia Hayes for her help in the data collection. Kevin McLin and Anne Metevier provided valuable comments on drafts of this paper. Doug Lombardi gave useful advice on statistics. Mel Sabella assisted with some of the interviews. Of course, none of this would be possible without the participation of students in the CSU courses.

NOTES

Note 1: Although a newer edition is now available, the first edition was used in our course at the time of data collection.

Note 2: masteringastronomy.com.

Note 3: gtn.sonoma.edu.

Note 4: 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.

Appendix: Detailed Tables for Sections 3–6

These tables correspond with the summary tables in the main body of the paper (e.g., Tables 3.1 and A3.1, etc.) Appendix tables include the original question, the answer (in bold if short 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.

3. CHEMICAL ELEMENTS

Table A3.1. Final Exam: Origin of Chemical Elements (Essay)

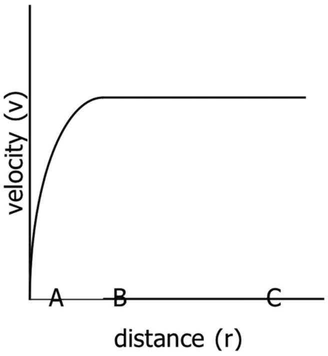
Question: Our bodies (and other living things on Earth) contain several chemical elements, including: hydrogen, oxygen, carbon, and iron. Discuss how each of these elements was formed and came to be in our bodies.

Answer: The lightest elements, including hydrogen, were made when the universe was a few minutes old and a few million degrees in temperature during Big Bang nucleosynthesis. Heavier elements, including carbon, oxygen, and iron were made in the cores of massive stars through nuclear fusion in the death stages of the star's lifecycle. (Oxygen was made in abundance in Earth's atmosphere by (plant) life through photosynthesis. All of the elements in our bodies are taken in from our environment but have been around for much longer, just in a different form.)

	Fall 2008 $N = 10$	**Spring 2009 $N = 9$**	**Spring 2010 $N = 13$**	**Fall 2010 $N = 13$**	**Spring 2011 $N = 13$**	**Total $H = 4.63$ $p = 0.33$ $N = 58$**
C	**3 (30%)**	**2 (22%)**	**0 (0%)**	**1 (8%)**	**5 (38%)**	**14 (24%)**
I	2 (20%)	3 (33%)	6 (46%)	7 (%54)	2 (15%)	19 (33%)
P	4 (40%)	3 (33%)	4 (31%)	4 (31%)	4 (31%)	17 (29%)
W	0 (0%)	0 (0%)	1 (8%)	0 (0%)	2 (15%)	5 (9%)
T	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
NS	0 (0%)	0 (0%)	2 (15%)	0 (0%)	0 (0%)	0 (0%)
NR	1 (10%)	1 (11%)	0 (0%)	1 (8%)	0 (0%)	3 (5%)

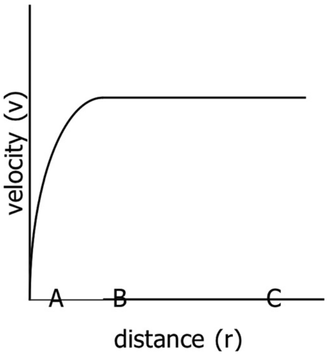
4. DARK MATTER

Table A4.1. Lab 8 pretest, Part A: Reading Rotation Curves
Question: What does this figure tell you about how the speeds of stars far from the center of the galaxy compare to the speeds of stars close to the center of the galaxy?
Answer: Stars far from the center are moving faster than stars in the center.



	Fall 2008 $N = 10$	Spring 2009 $N = 7$	Spring 2010 $N = 7$	Fall 2010 $N = 11$	Spring 2011 $N = 12$	Total $H = 2.56$ $p = 0.63$ $N = 47$
C	**4 (40%)**	**3 (43%)**	**4 (57%)**	**6 (55%)**	**4 (33%)**	**21 (45%)**
I	0 (0%)	2 (29%)	1 (14%)	1 (9%)	0 (0%)	4 (9%)
P	3 (30%)	1 (14%)	1 (14%)	1 (9%)	1 (8%)	7 (15%)
W	3 (30%)	1 (14%)	1 (14%)	2 (18%)	6 (50%)	13 (28%)
T	0 (0%)	0 (0%)	0 (0%)	1 (9%)	0 (0%)	1 (2%)
NS	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
NR	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (8%)	1 (2%)

Table A4.2 Lab 8 pretest, Part B: Reading Rotation Curves
Question: Rank the speeds of stars at distances A, B, and C
Answer: $A < B = C$



	Fall 2008 $N = 10$	**Spring 2009 $N = 7$**	**Spring 2010 $N = 7$**	**Fall 2010 $N = 11$**	**Spring 2011 $N = 12$**	**Total $H = 3.52$ $p = 0.47$ $N = 47$**
C	**2 (20%)**	**4 (58%)**	**4 (58%)**	**3 (27%)**	**4 (33%)**	**17 (36%)**
I	2 (20%)	1 (14%)	1 (14%)	3 (27%)	1 (8%)	8 (17%)
P	5 (50%)	1 (14%)	2 (28%)	4 (36%)	2 (17%)	14 (30%)
W	1 (10%)	1 (14%)	0 (0%)	1 (9%)	2 (17%)	5 (11%)
T	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
NS	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
NR	0 (0%)	0 (0%)	0 (0%)	0 (0%)	3 (25%)	3 (6%)

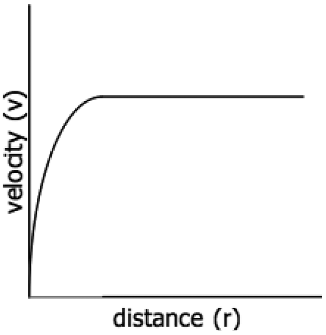
Table A4.3. Lab 8 pretest, Part C: Dark Matter and Rotation Curves
Question: Explain why the rotation curves of spiral galaxies like the one shown above are evidence for dark matter.
Answer: The gravitational force from the visible mass is not enough to cause the observed motion. There must be dark matter providing mass also in order to cause the observed rotation curves.

	Fall 2008 $N = 10$	**Spring 2009 $N = 7$**	**Spring 2010 $N = 7$**	**Fall 2010 $N = 11$**	**Spring 2011 $N = 12$**	**Total $H = 5.60$ $p = 0.23$ $N = 47$**
C	**1 (10%)**	**2 (29%)**	**2 (29%)**	**1 (9%)**	**0 (0%)**	**6 (13%)**
I	2 (20%)	0 (0%)	1 (14%)	6 (55%)	2 (17%)	11 (23%)
P	0 (0%)	2 (29%)	2 (29%)	1 (9%)	1 (8%)	6 (13%)
W	5 (50%)	1 (14%)	2 (29%)	3 (27%)	3 (25%)	14 (30%)
T	1 (10%)	1 (14%)	0 (0%)	0 (0%)	0 (0%)	2 (4%)
NS	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
NR	1 (10%)	1 (14%)	0 (0%)	0 (0%)	6 (50%)	8 (17%)

Table A4.4. Exam 3. Rotation Curves of Spiral Galaxies (Essay)

Question: Sketch a rotation curve for a typical spiral galaxy. Be sure to label the axes. How do the speeds of stars far from the center of the galaxy compare to the speeds of stars close to the center of the galaxy?

Answer: The velocities of stars far from the center of the galaxy are faster than those of stars close to the center. As distance increases the velocities of stars increase to a certain point and then they remain constant.



	Fall 2008 $N = 9$	**Spring 2009 $N = 9$**	**Spring 2010 $N = 12$**	**Fall 2010 $N = 13$**	**Spring 2011 $N = 13$**	**Total $H = 1.40$ $p = 0.84$ $N = 56$**
C	**1 (11%)**	**2 (22%)**	**2 (17%)**	**3 (23%)**	**4 (31%)**	**12 (21%)**
I	1 (11%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (2%)
P	5 (56%)	5 (56%)	6 (50%)	8 (62%)	6 (46%)	30 (54%)
W	2 (22%)	2 (22%)	4 (33%)	2 (15%)	3 (23%)	13 (23%)
T	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
NS	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
NR	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)

Table A4.5. Exam 3. Dark Matter and Rotation Curves (Essay)

Question: Explain why the rotation curves of spiral galaxies are evidence for dark matter, i.e., Explain the steps you would take to measure the amount of dark matter in a spiral galaxy.

Answer: We measure the total gravitational mass from the rotation curves: the faster something is moving, the greater the mass encircled. We measure the luminous mass from a plot of brightness vs. radius. A spiral galaxy has mass distributed throughout. The mass from just the visible parts of the galaxies is a small fraction compared to the total gravitational mass. Therefore, there must be dark matter providing mass also in order to cause the observed rotation curves.

	Fall 2008 $N = 9$	**Spring 2009 $N = 9$**	**Spring 2010 $N = 12$**	**Fall 2010 $N = 13$**	**Spring 2011 $N = 13$**	**Total $H = 1.48$ $p = 0.83$ $N = 56$**
C	**1 (11%)**	**2 (22%)**	**1 (8%)**	**4 (31%)**	**1 (8%)**	**9 (16%)**
I	5 (56%)	4 (44%)	4 (33%)	5 (38%)	7 (54%)	25 (45%)
P	2 (22%)	1 (11%)	1 (8%)	2 (15%)	3 (23%)	9 (16%)
W	1 (11%)	2 (22%)	4 (33%)	1 (8%)	2 (15%)	10 (18%)
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%)	2 (17%)	1 (8%)	0 (0%)	3 (5%)

Table A4.6. Exam 3: Dark Matter (T/F)
Question: Dark matter is the matter that we have identified from its gravitational effects but we cannot see in any wavelengths of light. **True** / False

	Fall 2008 $N = 9$	**Spring 2009 $N = 9$**	**Spring 2010**	**Fall 2010 $N = 13$**	**Spring 2011 $N = 13$**	**Total $H = 0.48$ $p = 0.92$ $N = 44$**
T	**8 (89%)**	**8 (89%)**	—	**13 (100%)**	**11 (85%)**	**40 (91%)**
F	1 (11%)	0 (0%)	—	0 (0%)	2 (15%)	3 (7%)
NR	0 (0%)	1 (11%)	—	0 (0%)	0 (0%)	1 (2%)

Table A4.7. Final Exam: Dark Matter (T/F)
Question: Dark matter is the matter that we have identified from its gravitational effects but we cannot see in any wavelengths of light. **True** / False

	Fall 2008	**Spring 2009**	**Spring 2010**	**Fall 2010**	**Spring 2011 $N = 13$**	**Total $N = 13$**
T	—	—	—	—	**10 (77%)**	**10 (77%)**
F	—	—	—	—	3 (23%)	3 (23%)
NR	—	—	—	—	0 (0%)	0 (0%)

Table A4.8. Final Exam: Dark Matter (MC)
Question: The shape of our Galaxy's rotation curve implies the existence of

a. a mysterious, unknown force.
b. **dark matter.**
c. dark energy.
d. pulsars.
e. missing gas and dust.

	Fall 2008 $N = 10$	**Spring 2009**	**Spring 2010**	**Fall 2010**	**Spring 2011**	**Total $N = 10$**
A	1 (10%)	—	—	—	—	1 (10%)
B	**5 (50%)**	—	—	—	—	**5 (50%)**
C	3 (30%)	—	—	—	—	3 (30%)
D	0 (0%)	—	—	—	—	0 (0%)
E	1 (10%)	—	—	—	—	1 (10%)
NR	0 (0%)	—	—	—	—	0 (0%)

5. DARK ENERGY

Table A5.1. Exam 3. Dark Energy (MC)

Question: Which of the following best summarizes what we mean by dark energy?

a. It is a type of energy that is associated with the “dark side” of the force that rules the universe.
b. It is the energy of black holes.
c. It is the energy contained in dark matter.
d. **It is a name given to whatever might be responsible for causing the expansion of the universe.**

	Fall 2008 $N = 9$	**Spring 2009**	**Spring 2010 $N = 12$**	**Fall 2010 $N = 13$**	**Spring 2011 $N = 13$**	**Total $H = 3.03$ $p = 0.39$ $N = 47$**
A	0 (0%)	—	1 (8%)	0 (0%)	0 (0%)	1(2%)
B	0 (0%)	—	0 (0%)	1 (8%)	0 (0%)	1 (2%)
C	0 (0%)	—	2 (17%)	4 (31%)	1 (8%)	7 (15%)
D	**9 (100%)**	—	**9 (75%)**	**8 (62%)**	**12 (92%)**	**38 (81%)**
NR	0 (0%)	—	0 (0%)	0 (0%)	0 (0%)	0 (0%)

6. OVERALL COMPOSITION

Table A6.1. Exam 3: Overall Composition of Universe (MC)

Question: The overall composition of the universe is

a. 100% ordinary matter
b. 2% ordinary matter, 98% exotic dark matter
c. 15% ordinary matter, 85% exotic dark matter
d. **4% ordinary matter, 23% exotic dark matter, 73% dark energy**

	Fall 2008 $N = 9$	**Spring 2009 $N = 9$**	**Spring 2010 $N = 12$**	**Fall 2010 $N = 13$**	**Spring 2011 $N = 13$**	**Total $H = 5.95$ $p = 0.20$ $N = 56$**
A	0 (0%)	0 (0%)	1 (8%)	1 (8%)	0 (0%)	2 (4%)
B	2 (22%)	1 (11%)	4 (33%)	1 (8%)	0 (0%)	8 (14%)
C	0 (0%)	1 (11%)	3 (25%)	0 (0%)	4 (31%)	8 (14%)
D	**7 (78%)**	**7 (78%)**	**4 (33%)**	**11 (85%)**	**9 (69%)**	**38 (68%)**
NR	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)

Table A6.2. Final Exam: Overall Composition of Universe (MC)

Question: The overall composition of the universe is

a. 100% ordinary matter
b. 2% ordinary matter, 98% exotic dark matter
c. 15% ordinary matter, 85% exotic dark matter
d. **4% ordinary matter, 23% exotic dark matter, 73% dark energy**

	Fall 2008 $N = 10$	**Spring 2009**	**Spring 2010**	**Fall 2010** $N = 13$	**Spring 2011**	**Total** *KS-stat* **= 0.44** $p = 0.10$ $N = 23$
A	0 (0%)	—	—	0 (0%)	—	0 (0%)
B	4 (40%)	—	—	0 (0%)	—	4 (17%)
C	0 (0%)	—	—	0 (0%)	—	0 (0%)
D	**6 (60%)**	—	—	**13 (100%)**	—	**19 (83%)**
NR	0 (0%)	—	—	0 (0%)	—	0 (0%)

Table A6.3. Final Exam: Composition (Essay)

Question: Give one example of something in the universe that is not made of any chemical elements and how we know it exists.

Answer: Possible examples include, but are not limited to: dark matter (rotation curves, motions of galaxies in clusters, lensing), dark energy (accelerating expansion of the universe), subatomic particles (particle detectors).

	Fall 2008	**Spring 2009** $N = 9$	**Spring 2010** $N = 13$	**Fall 2010** $N = 13$	**Spring 2011** $N = 13$	**Total** $H = 3.08$ $p = 0.38$ $N = 48$
C	—	**6 (67%)**	**3 (23%)**	**7 (54%)**	**7 (54%)**	**23 (48%)**
I	—	0 (0%)	3 (23%)	3 (23%)	2 (15%)	8 (17%)
P	—	1 (11%)	1 (8%)	2 (15%)	3 (23%)	7 (15%)
W	—	2 (22%)	5 (38%)	1 (8%)	0 (0%)	8 (17%)
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%)	0 (0%)	1 (8%)	2 (4%)

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