Understanding Students' Difficulties with Cosmology: A Proposal to the I3 Graduate Research Fellowship Program

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Introductory astronomy courses attract approximately a quarter of a million college students each year in the United States (Fraknoi 2001). These students represent a wide cross-section of the American undergraduate population: 31% are non-Caucasian and 85% are non-STEM (science, technology, engineering, and mathematics) majors (Deming and Hufnagel 2001). Instructing these non-STEM majors is important because they include many future lawyers, journalists, business leaders, politicians, and teachers. For many of these students, introductory astronomy will be the last science course they ever take. The quality of their astronomy education may therefore have a lasting impact on their scientific literacies and attitudes toward science. Given the importance of these introductory astronomy classes, especially for non-STEM majors, they have been the focus of much work in the burgeoning field of astronomy education research (AER). Despite this focus, significant gaps in our knowledge remain. One of the most conspicuous is a lack of research on students' understandings of cosmology, the study of the origin, evolution, and fate of the universe as a whole. This omission is even more striking considering that cosmology is one of the most frequently taught topics in introductory astronomy (Slater *et al* 2001). This project is the first attempt to systematically investigate the difficulties students experience while studying cosmology in an introductory course aimed at non-STEM majors.

Our effort is a collaboration between researchers at the University of Colorado at Boulder and the University of Arizona. Colin Wallace, who is entering his fifth year of graduate school at CU-Boulder and for whom an I3 graduate research fellowship is sought, is leading the project. He is working under the guidance of Doug Duncan at CU-Boulder and Ed Prather at UA; other project members are Seth Hornstein (CU-Boulder), Gina Brissenden (UA), and Chris Impey (UA). This project is the basis for Wallace's Ph.D. dissertation. Ph.D. dissertations based on astronomy education research (AER) are supported by the Department of Astrophysical and Planetary Sciences (APS): In the spring of 2008, the APS faculty voted unanimously to approve AER topics as appropriate for dissertations. The APS department is able to provide the 25% matching funds requested by I3 since each year there are numerous TA positions available for graduate students; Wallace has been a full-time TA for every semester since he matriculated at CU-Boulder. Receiving an I3 graduate research fellowship will allow Wallace to devote more time to this project as he looks to complete his degree by May, 2011.

Previous investigations in both AER and physics education research have yielded many important results. One such result is our improved understanding of how students construct knowledge. Students do not enter the classroom as *tabula rasa*; they have their own intuitions about how the world works based on years of experience (diSessa 1993; McDermott 1991; Redish 1994). These intuitions constitute a collection of cognitive resources upon which students draw as they attempt to understand a particular phenomenon (diSessa 1993; Hammer *et al* 2005; Minstrell 1991). In many cases, students' views of the world are not robust, well-defined models. Rather, their mental models are the result of the in-the-moment, context-dependent activation (and suppression) of a suite of resources (diSessa 1993; Hammer *et al* 2005; Minstell 1991). In isolation, a resource is neither correct nor incorrect. However, it may be activated at inappropriate junctures.[1] In this framework, learning is understood as the process by which students organize and construct their own mental models of a topic (McDermott 1991; Redish 1994). The role of the instructor is to provide guidance and a class environment supportive of this process. Instructors must directly address the prior knowledge students bring to the classroom and emphasize the importance of "sense-making" to their students. Failure to do so often results in temporary, superficial learning (McDermott 1991; Minstrell 1991; Redish 1994). This constructivist view of learning has many practical applications. For example, the *Lecture-Tutorials in Introductory Astronomy* (Prather *et al* 2008) are specifically designed to address the most common student difficulties, as revealed by research. Each tutorial is a two to six page worksheet activity filled with Socratic dialogue-driven questions that a group of two to three students can complete in approximately fifteen minutes (Brogt 2007; Prather *et al* 2005). A tutorial helps students "make sense" of and construct their own mental models of a particular astronomical topic; this is accomplished by either drawing out and building upon students' correct intuitions (Clement, Brown, Zietsman 1989), or by making students realize when their intuitions are inappropriate via the elicit-confront-resolve method (McDermott 1991, based on the conceptual change model proposed by Posner *et al* 1982). This approach has met with dramatic success: Students in classes using the *Lecture-Tutorials* demonstrate learning gains significantly higher than their peers taking a similar, entirely lecture-based class (Prather *et al* 2005).

Currently, there are only two *Lecture-Tutorials* covering topics in cosmology, an abominably low number considering the importance of cosmology to astronomers (in introductory astronomy, cosmology may account for

1 For example, *closer means more* is an entirely valid resource to activate when thinking about why we get warmer as we approach a fire. It is not useful when reasoning about the cause of the seasons (Brogt 2007).

as much as a third of the class). Because cosmology is such a large, dynamic, ever-growing field, we must necessarily restrict our attention to a limited number of topics. We will focus on issues related to the expanding universe. The idea that the universe is expanding in size has been one of the dominant paradigms in cosmology since the 1920s. It also sits at the intersection of numerous cosmological theories and observations, including lookback times, distances and redshifts of galaxies, the Big Bang, and evidence for dark energy. These ideas are conceptually rich, commonly taught, and directly related to one another via the expanding universe model. This makes the expanding universe an obvious choice upon which to focus our investigation.

The goals of this project are to characterize students' difficulties with the expanding universe model and to develop tutorials designed to help students overcome these difficulties. Specifically, we will investigate and answer three questions:

- What does "understanding the expanding universe model" mean?
- What challenges do students encounter as they strive toward this understanding?
- How can introductory astronomy instructors foster their students' understandings?

Based on previous experiences teaching introductory astronomy to non-STEM majors, our collaboration has developed a preliminary list of what comprises "understanding the expanding universe model." A student who understands the expanding universe can

- explain how this model is consistent with a universe with neither a center nor an edge;
- state what about the universe is expanding;
- evaluate standard analogies for the expanding universe (such as the inflating balloon and the rising raisin bread) and explain which properties of the universe are and are not reflected by these analogies;
- motivate the Big Bang model by running the expansion backward in his or her mind
- describe the Big Bang as the expansion of the universe from an initial hot, dense state, rather than the explosion of pre-existing matter into empty space;
- describe why the cosmic microwave background and the abundance of helium are observational evidence for the Big Bang;
- use the idea of an expanding universe to qualitatively relate the distance light has traveled to reach us from a far away galaxy to its present distance from us and the age at which we see the galaxy;
- explain the evidence for an accelerating rate of expansion.

We do not assert this list is final or authoritative. Since we will survey faculty about what they expect out of their students when they teach cosmology, we expect its contents to change as the project progresses. We will adjust this list until its contents are both reasonable for non-STEM majors and well-matched to what many instructors teach in introductory astronomy.

The final two questions will be answered by the data we gather from students. The small number of previous AER studies on cosmology offer some guidance as to where students may struggle. Students may not know the universe is expanding (Lightman and Miller 1989). They may think the Big Bang refers to the formation of the Solar System (Prather, Slater, and Offerdahl 2002; Simonelli and Pilachowski 2003). They may also envision the Big Bang as the explosion of pre-existing matter into empty space (Prather, Slater, and Offerdahl 2002). These results, combined with our experiences teaching cosmology, suggest the following questions should evoke a wide range of non-expert-like responses from students:

1) What does the term "universe" mean to you? Please describe what you think the universe is with as much detail as you can. What objects/things are included (i.e. exist) within the universe? Is there anything excluded (i.e. does not exist within) the universe? If possible, use a drawing to help explain your ideas.
2) Do you think the universe has a shape? If so, describe and/or draw it. If not, describe why not.
3) Do you think there is a center to the universe? Why or why not? If the universe does have a center, what do you think is there? Is there anything about the center which distinguishes it from the rest of the universe?
4) Do you think the universe has an edge? Why or why not? If the universe does have a edge, what do you think is there? Is there anything about the edge which distinguishes it from the rest of the universe?
5) What do you think astronomers mean when they say "the universe is expanding"? Please describe your thinking with as much detail as you can. If possible use a drawing to help explain your ideas. Is the universe expanding into anything? What in the universe is expanding?
6) Have you ever heard of the Big Bang Theory? Please explain what you think the Big Bang theory is with

as much detail as you can. If possible, use a drawing to help explain your ideas.

7) Have you ever heard of the cosmic microwave background radiation? Please explain what you think the cosmic microwave background radiation is with as much detail as you can. If possible, use a drawing to help explain your ideas.
8) Have you ever heard of spacetime? What does the term spacetime mean to you?

These questions form the core of the survey we are developing for the first of the project's two phases.

In Phase I of the project, we will determine what students are actually learning about the expanding universe in their introductory astronomy course. CU-Boulder offers two introductory astronomy courses for non-STEM majors in which cosmology is taught: ASTR 1020 and ASTR 1120.[2] We will survey students in these classes each semester. In addition to questions on cosmology, the surveys will ask students to describe any previous high school or college astronomy course they have taken; this allows us to determine if the responses of students who previously took astronomy are different from those who have not. Additionally, we will interview a small number of volunteering students from each class. Each interview will be based loosely on the survey questions. These interviews allow us to probe students' ideas more in-depth. They also help us understand how students are interpreting our questions. The results of these interviews and surveys will inform us about the range of students' ideas. This, in turn, will help us refine and develop future surveys and assessments on the expanding universe, as well as design tutorials that address the most common student difficulties. Phase I should last two to three semesters and involve between 600 and 1000 students.

In Phase II of the project, we will create, test, and refine tutorials. The tutorials we develop will follow the well-established structure of earlier *Lecture-Tutorials*: They will be designed to help students construct their own understandings of the expanding universe and they will focus on resolving the most common difficulties we uncover in Phase I. The effectiveness of the tutorials will be evaluated by administering surveys and assessments based on the results of Phase I. We will compare these results to those from classes not using tutorials. These results, coupled with classroom observations of the tutorials in action, will tell us which parts of the tutorials require modification. Phase II will last two to three semesters and involve up to 1000 students.

This project is both necessary and timely. As described above, this research will help fill a void in AER that has so far been left empty. The results of this project will also be significant for how cosmology is taught in introductory astronomy. Because cosmology is such a common topic, introductory astronomy instructors at all levels, from graduate students to tenured professors, will benefit from an increased understanding of where and why students struggle, as well as how they can help their students. Students will also profit from improved instruction. At CU-Boulder alone, almost 600 students take ASTR 1020 or ASTR 1120 each semester. CU-Boulder is unusual in that the APS department offers a course completely devoted to teaching non-STEM majors cosmology (ASTR 2010); these students should also benefit from this research. Furthermore, STEM majors encounter cosmology in both ASTR 1040 and ASTR 3740, which are offered each spring - and, as Zeilik and Morris (2003) have found, STEM majors often have similar conceptual difficulties as non-STEM majors. These courses offer natural avenues for expanding the results of this research. But even if we only focus on those students taking either ASTR 1020 or ASTR 1120, the results of this study may positively impact over a thousand CU-Boulder students each year.

This study is also significant for STEM education beyond CU-Boulder. The astronomical community in general is showing an increased interest in education issues; this is demonstrated by the American Astronomical Society's recent decision to take over publication of the *Astronomy Education Review.* The most recently completed Decadal Survey also emphasized improving the scientific understanding of students taking introductory astronomy (National Research Council 2001). The Decadal Survey noted that introductory astronomy is important since it is the final science course taken by many future teachers, journalists, and other professionals charged with communicating science to others (National Research Council 2001). Any effort to improve introductory astronomy may thus also contribute to improved science literacy among the general public as well as improved education at the K-12 level - the latter being an issue of need highlighted by numerous recent reports (National Academy of Sciences, National Academy of Engineering, and the Institute of Medicine 2007; National Commission on Mathematics and Science Teaching for the 21st Century 2000). As the final science course many non-STEM majors will ever take, introductory astronomy has the potential to dramatically affect many people's opinion toward and understanding of science in general.

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2 ASTR 1020 and ASTR 1120 have the same content. ASTR 1020 differs from ASTR 1120 in that it has a prerequisite (ASTR 1010) and offers recitation sections.

References Cited

Brogt, E., "A Theoretical Background on a Successful Implementation of Lecture-Tutorials", *Astron. Educ. Rev.* **6**(1) 50-8 (2007).

Clement, J., D. E. Brown, and A. Zietsman, "Not all preconceptions are misconceptions: finding 'anchoring conceptions' for grounding instruction of students' intuitions", *Int. J. Sci. Educ.* **11** 554-65 (1989).

Deming, G. and B. Hufnagel, "Who's Taking ASTR 101?", *Phys. Teach.* **39**(6) 368-9 (2001).

diSessa, A. A., "Toward an Epistemology of Physics", *Cog. Instruct.* **10**(2 & 3) 105-225 (1993).

Fraknoi, A., "Enrollments in Astronomy 101 Course: An Update", *Astron. Educ. Rev.* **1**(1) 121-3 (2001).

Hammer, D., A. Elby, R. E. Scherr, and E. F. Redish, "Resources, framing, and transfer", in *Transfer of Learning from a Modern Multidisciplinary Perspective*, ed. J. Mestre (Scottsdale, AZ, Information Age Publishing, 2005), 89-120.

Lightman, A. P. and J. D. Miller, "Contemporary Cosmological Beliefs", *Soc. Stud. Sci.* **19** 127-36 (1989).

McDermott, L. C. , "Millikan Lecture 1990: What we teach and what is learned - Closing the gap", *Am. J. Phys.* **59**(4) 301-15 (1991).

Minstrell, J., "Facets of students' knowledge and relevant instruction", in *Research in Physics Learning: Theoretical Issues and Empirical Studies : Proceedings of an International Workshop Held at the University of Bremen, March 4-8, 1991*, ed. R. Duit, F. Goldberg, and H. Niedderer (Kiel, Germany, Institut für die Pädagogik der Naturwissenschaften an der Universität Kiel, 1992), 110-28.

National Academy of Sciences, National Academy of Engineering, and the Institute of Medicine, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future* (Washington, DC, National Academies Press, 2007).

National Commission on Mathematics and Science Teaching for the 21st Century, *Before It's Too Late: A Report to the Nation from the National Commission on Mathematics and Science Teaching for the 21st Century* (Washington, DC, US Department of Education, 2000).

National Research Council, *Astronomy and Astrophysics in the New Millennium* (Washington, DC, National Academy Press, 2001).

Posner, G. J., K. A. Strike, P. W. Hewson, and W. A. Gertzog, "Accommodation of a Scientific Conception: Toward a Theory of Conceptual Change", *Sci. Educ.* **66**(2) 211-27 (1982).

Prather, E. E., T. F. Slater, J. P. Adams, J. M. Bailey, L. V. Jones, and J. A. Dostal, "Research on a Lecture-Tutorial Approach to Teaching Introductory Astronomy for Non-Science Majors", *Astron. Educ. Rev.* **3**(2) 122-36 (2005).

Prather, E. E., T. F. Slater, J. P. Adams, G. Brissenden, J. A. Dostal, and the CAPER team, *Lecture-Tutorials for Introductory Astronomy* (San Fransisco, Pearson Addison-Wesley, 2008).

Prather, E. E., T. F. Slater, and E. G. Offerdahl, "Hints of a Fundamental Misconception in Cosmology", *Astron. Educ. Rev.* **1**(2) 28-34 (2002).

Redish, E. F., "Implications of cognitive studies for teaching physics", *Am. J. Phys.* **62**(9) 796-803 (1994).

Simonelli, G. and C. A. Pilachowski, "First-Year College Students' Ideas About Astronomy: A Pilot Study", *Astron. Educ. Rev.* **2**(2) 166-71 (2003).

Slater, T., J. P. Adams, G. Brissenden, and D. Duncan, "What Topics Are Taught in Introductory Astronomy Courses?", *Phys. Teach.* **39**(1) 52-5 (2001).

Zeilik, M. and V. J. Morris, "An Examination of Misconceptions in an Astronomy Course for Science, Mathematics, and Engineering Majors", *Astron. Educ. Rev.* **1**(2) 101-19 (2003).