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

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Introductory astronomy (hereafter ASTR 101) reaches approximately 250,000 American college students annually (Fraknoi 2001). These students, many of whom will become teachers, business leaders, and politicians, represent a broad cross-section of the nation's undergraduate population (Deming and Hufnagel 2001; Rudolph et al 2010). Since ASTR 101 will be the last science course many of these students ever take, the growing field of astronomy education research (AER) has focused much of its efforts on improving student learning at the ASTR 101 level. One area requiring further attention is cosmology. Cosmology is the study of the history, evolution, and fate of the universe as a whole and, as such, is one of the most commonly taught topics in ASTR 101 (Slater et al 2001). Yet, with the exception of a handful of studies (Comins 2001; Lightman and Miller 1989; Lightman, Miller, and Leadbeater 1987; Prather, Slater, and Offerdahl 2002; Simonelli and Pilachowski 2003), little work has been done to investigate where and why ASTR 101 students struggle when they study cosmology. This project is one of the first large-scale efforts to study ASTR 101 students' understandings of cosmology and to develop research-validated lecture-tutorials to help students better learn cosmology.

This proposal is a request for a second iSTEM graduate fellowship to help support Colin Wallace, a doctoral student in the Department of Astrophysical and Planetary Sciences (APS), during the 2010-2011 academic year. Colin's project is the culmination of the first AER Ph.D. dissertation approved by the APS Department. This project is a collaboration between the University of Colorado at Boulder and the University of Arizona and is supervised by Doug Duncan (CU) and Ed Prather (AZ).

Colin's dissertation has two key questions: 1) Which concepts do introductory astronomy (hereafter ASTR 101) students struggle with when they study cosmology and why? and 2) Can we design lecture-tutorials to help ASTR 101 students overcome these difficulties?

Probing Students' Ideas About Cosmology:

To answer the first question, we developed and simultaneously administered four different surveys in ASTR 101 classes at both CU and Arizona. These surveys focus on four key constructs, where "construct" is defined as "the concept or characteristic that a test is designed to measure" (AERA/APA/NCME 1999; see also Wilson 2005). The four constructs are:

1) *Models of the Expanding Universe*: This construct focuses on students' conceptualizations of the expanding universe and the Big Bang.

2) *Hubble Plots*: This construct focuses on whether or not students can use Hubble plots to reason about the age and expansion rate of the universe.

3) *Evolving Universe*: This construct looks at whether or not students can explain how the universe has changed over time as a result of its expansion.

4) *Dark Matter*: This construct probes whether a student can reconstruct the causal chain of reasoning linking a galaxy's observed rotation curve with the distribution of matter within the galaxy.

Each of the four surveys focuses on one of these constructs. We developed these surveys in a systematic manner by following Wilson's (2005) four building blocks for survey development. First, we created construct maps for each construct, which are hypothetical tabular representations of how students vary along each construct. See Table 1 for an example construct map for the construct *Mental Models of the Expanding Universe*. Second, we wrote and selected items for each survey that help us distinguish between students at different levels of the construct. Third, we thought about how each item should be scored and created scoring rubrics for each survey. Fourth, we applied standard psychometric measurement models, such as classical test theory (CTT) and item response theory (IRT), to our scored responses (see Hambleton and Jones 1993 for a comparison of CTT and IRT). This sequence helps ensure that each survey's construct definition, items, scoring procedure, and score interpretation are tightly-linked. This sequence also helps us construct validity arguments for each survey, since the validity of a survey is intimately related to how one interprets it (AERA/APA/NCME 1999). Colin learned about these methods of survey development, CTT, and IRT as part of a two-semester graduate-level course sequence he took from the School of Education during the 2009-2010 academic year. Colin was able to devote the time necessary to take these classes in part due to the support he received from his 2009-2010 iSTEM fellowship.

These written surveys are augmented by classroom observations and cognitive interviews Colin conducted with individual students. While observing three different ASTR 101 classes at CU during the fall 2009 semester, Colin developed a formal procedure for the classroom observations he's currently conducting of three ASTR 101 courses at CU. In this procedure, Colin writes down each topic the instructor covers, how long the
instructor spends on that topic, how much detail the instructor provides, and how the instructor teaches the topic. Colin pays special attention to the number and nature of interactive teaching strategies employed by each instructor, since these techniques have been linked to high student learning gains (Hake 1998; Prather et al. 2009). He developed a rubric for codifying his observations of interactive teaching, based on his prior observations and the research of others (e.g. Turpen and Finkelstein 2009). These classroom observations help Colin understand what students have ostensibly learned in class and it helps him make sense of any patterns he might observe in students' survey responses.

Table 1. Construct map for the Mental Models of the Expanding Universe construct. Differences between a level and its adjacent lower level are denoted by underlined words.

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
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<tbody>
<tr>
<td>4</td>
<td>The student <strong>correctly</strong> states that the universe is physically expanding in size over time. The student <strong>correctly</strong> states that only galaxies are moving apart from one another due to expansion. The student <strong>correctly</strong> claims that the universe has no center. The student <strong>correctly</strong> claims that the universe has no edge. The student <strong>correctly</strong> describes the Big Bang as the beginning of expansion.</td>
</tr>
<tr>
<td>3</td>
<td>The student <strong>correctly</strong> states that the universe is physically expanding in size over time. The student <strong>correctly</strong> states that all objects in the universe are moving apart from one another due to expansion. The student <strong>correctly</strong> claims that the universe has no center. The student <strong>correctly</strong> claims that the universe has no edge. The student <strong>may</strong> describe the Big Bang as an explosion <strong>or</strong> as the beginning of expansion.</td>
</tr>
<tr>
<td>2</td>
<td>The student <strong>correctly</strong> states that the universe is physically expanding in size over time. The student <strong>incorrectly</strong> states that all objects in the universe are moving apart from one another due to expansion. The student <strong>incorrectly</strong> claims that the universe has a center. The student <strong>incorrectly</strong> claims that the universe has an edge. The student <strong>incorrectly</strong> describes the Big Bang as an explosion but <strong>not</strong> as the beginning of something smaller than the universe (e.g. the Solar System, Galaxy, etc.).</td>
</tr>
<tr>
<td>1</td>
<td>The student <strong>incorrectly</strong> states that the universe is not physically expanding in size over time. The student <strong>may or may not</strong> claim that the universe has a center. The student <strong>may or may not</strong> claim that the universe has an edge. The student <strong>incorrectly</strong> describes the Big Bang as an explosion and/or as the beginning of something smaller than the universe (e.g. the Solar System, Galaxy, etc.).</td>
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To date, Colin has conducted cognitive interviews with ten ASTR 101 students. During these hour-long think-aloud interviews, Colin has the interviewee answer every question to three of the four surveys. As part of his survey methodology coursework, Colin constructed an interview protocol based on the best-practices recommendations of Patton (1980) and Wills (2005). These cognitive interviews serve two purposes: 1) They provide additional evidence about what students find difficult about cosmology; and 2) They help Colin detect survey questions that are unclear or repeatedly misinterpreted by ASTR 101 students.

**Lecture-Tutorial Development:**

Colin has also coauthored a new suite of lecture-tutorials devoted to cosmology. Each lecture-tutorial was designed based on the same constructivist framework underlying the development of the highly successful Lecture-Tutorials for Introductory Astronomy. (Prather et al 2005; Prather et al 2008). A lecture-tutorial is a two to six page worksheet of Socratic dialogue-driven questions that helps students construct their own understandings of a topic that research has shown students struggle with (Prather et al 2005). Below is a brief description of the content and goals of each of the five new cosmology lecture-tutorials.

1) **Making Sense of the Universe and Expansion:** This tutorial helps students make sense of the balloon analogy for the expanding universe.

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2) **Hubble's Law**: This tutorial helps students understand Hubble's law and Hubble plots for the expansion of the universe.

3) **Expansion, Lookback Times, and Distances**: This tutorial helps students understand the effect the expansion of the universe has on lookback times.

4) **The Big Bang**: This tutorial helps students realize that the Big Bang refers to the expansion of space from an initially hot and dense state and not to the explosion of pre-existing matter into empty space.

5) **Dark Matter**: This tutorial helps students understand one piece of evidence for the existence of dark matter in spiral galaxies.

These five lecture-tutorials were developed following a procedure similar to Prather et al's (2005) description of the development of the original Lecture-Tutorials. We selected the topics for the five cosmology lecture-tutorials based on students' responses to a preliminary survey administered in the fall of 2008, our knowledge of common ASTR 101 cosmology topics, and our experiences teaching ASTR 101 students. Colin used the first drafts of these lecture-tutorials in a summer ASTR 101 course he taught from July-August 2009.

These cosmology lecture-tutorials have since been significantly modified. Some modifications were made in response to feedback we received from our colleagues in order to refine the clarity, content, and scope of the tutorials. Other modifications were made in response to our observations of students working on the tutorials. Like the original Lecture-Tutorials, we want the cosmology lecture-tutorials to function in large enrollment (approximately 100+ students) classes. We assume if they can work in this environment, they can work in smaller classes. In order to function in large classes, the cognitive steps between each question must be small and students must be able to progress through the tutorials with minimal instructor assistance (Prather et al 2005). Based on these criteria, we flagged a question for revision if it confused many students, led many students to the wrong answer (either on the tutorial itself or on one of our assessment questions), or required the instructor to help many groups of students. Finally, we have also revised the tutorials in conjunction with revisions to ensure that they are linked to the same constructs. We expect this iterative procedure will yield cosmology lecture-tutorials that are suitable for publication in future editions of the Lecture-Tutorials for Introductory Astronomy (Prather et al 2008).

**Preliminary Outcomes:**

To date, each of the five cosmology lecture-tutorials is in its third draft version or beyond. The four assessment surveys are currently in their eighth version and we have evidence supporting the validity of all but three questions.

In addition to Colin's summer course, these tutorials have been used in large lecture hall ASTR 101 classes offered at both CU and Arizona, including an 800 student class currently being taught by Ed Prather at Arizona. By the end of the spring 2010 semester, approximately 1450 students will have used these tutorials.

Do these lecture-tutorials have any effect on students? A preliminary analysis indicates the answer is "yes." For example, 65% of students who used the lecture-tutorials were able, by the end of the fall 2009 semester, to correctly identify the rotation curve of a spiral galaxy. Rotation curves were emphasized in all classes (both using and not using lecture-tutorials). Yet, of all the students not using the lecture-tutorials, only 19% could select the correct rotation curve by the end of the semester. While results such as these are suggestive about the efficacy of the tutorials, additional work must be done before we can give a definitive answer to this question.

These lecture-tutorials and our research into students' difficulties with cosmology appear to be meeting a need in the broader community. In addition to the poster he presented at the inaugural STEM Education Symposium at CU-Boulder, Colin also presented an updated poster and gave a contributed talk at the January 2010 meeting of the American Astronomical Society. Several attendees requested copies of the tutorials and/or offered to help the project by using the surveys and tutorials in their classes. In April 2010, Colin will take part in a roundtable discussion on the use of IRT in his research at the International Objective Measurement Workshop. Finally, Colin will presented his research as one of the invited speakers to the January 2011 meeting of the American Association of Physics Teachers.

**Next Steps:**

What work will Colin do in the next year? His main goals are to finalize the lecture-tutorials and surveys, and publish my results and write my dissertation. In addition to giving the talks mentioned above, Colin will
continue to work on writing and revising the scoring rubrics for the surveys. Colin and Doug Duncan will then score the surveys independently. This allows us to check for inter-rater reliability. This task will dominate much of the summer of 2010. Also during this time, Colin will work with Ed Prather to revise the tutorials and surveys based on the data collected from previous semester. These revisions will be ready to implement by the fall of 2010. We will once again survey classes at CU and Arizona, some of which will not use the tutorials and will thus serve as important controls in our study. We will also survey classes outside of CU and Arizona (some of which will use the tutorials and some of which will not) during the fall 2010. The data we collect will be analyzed by spring 2011, which is when we plan to publish the results of this study. Colin will also write and defend his dissertation during the spring 2011 so that he can graduate by that May.

Colin's Need for a Second iSTEM Grant:

Receiving a second iSTEM graduate fellowship will greatly help Colin meet the milestones on the above timeline. We request he receive a 25% fellowship for the 2010-2011 academic year. No summer support is necessary since, during that time, he is supported by NSF grant No. 0715517, a CCLI Phase III Grant for the Collaboration of Astronomy Teaching Scholars (CATS). This money is available to support Colin during the summer because he is working with researchers at the University of Arizona. As for the remaining 25% of Colin's salary during the academic year, we are currently exploring whether or not the matching funds could come from the CATS grant; this is contingent upon CU waiving any overhead fees. Colin also applied for a dissertation fellowship from CU, which was, unfortunately, not awarded. Ultimately, Colin can obtain the matching funds even though the specific source is currently unclear. If none of these funding sources come through, Colin can support himself through a TA appointment offered by the APS Department. However, given the amount of work that remains to be done over the next year, Colin is best served by being able to concentrate his energies on research, which is why we request a second iSTEM fellowship for him.
References


