Astronomy Education Research:

Developmental History of the Field and Summary of the Literature

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This is a commissioned paper for the

National Research Council Board on Science Education's

Committee on the Status, Contributions, and Future Directions of Discipline Based Education Research

January 2011

Abstract

Although astronomy topics have been included in K-12 education research for decades, astronomy education research as a field of discipline-based education research is relatively new. Driven by an interest in improving the general education, introductory course for non-science majors ("ASTRO 101"), astronomy education research is led by scholars with significant expertise in astronomy content. In this review, I outline the history of this field through looking at graduate degrees earned, faculty involved, and major milestones such as the creation of *Astronomy Education Review*. I also review the current status of the field, building upon a previous review by Bailey and Slater (2003). Six typologies are described: identifying students' preconceptions; studying curricular and instructional effectiveness; assessment and instrumentation; relevant issues from high school; upper-division and graduate coursework; and investigations that go beyond knowledge. Within the description of each typology, I highlight common methodologies and results as well as point out limitations or weaknesses. I end the review with recommendations for the future of astronomy education research, including the need for more robust research design and analysis methods and possible research lines for longitudinal research, including learning progressions, and more in the affective, motivational, and related domains.

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Astronomy is one of the oldest scientific fields, yet it continues to capture the imagination of the young and old alike. It is one of the few – perhaps the only – science in which there is a sizeable population of amateurs who are able to contribute in meaningful ways to the growth of the field. This is exemplified by the American Association of Variable Star Observers (AAVSO), founded as a way of bringing together amateur astronomers to coordinate observing efforts across the country and, eventually, the globe. Professional astronomers frequently use data from the AAVSO to support their own research. Citizen science projects, such as SETI@Home and Galaxy Zoo (Raddick et al., 2010), have expanded the reach of astronomy to even more people; similar projects in other disciplines are also generating public excitement, especially now that the Internet has made participation easier than ever (e.g., Audubon's Christmas Bird Count or Boston Museum of Science's Firefly Watch).

Nearly anyone can contribute to citizen science projects; that is, in fact, the goal. The same is not true for professional or academic research areas, where appreciable education and experience is required in order to be considered a scholar in the field (Mayer, 1992). In the past, there was a clear distinction between education research and science research; one need only look at the departmental home of the scholar. This is no longer the case, as science content experts take on education research.

For the purposes of this review, I will define *discipline-based education research* (DBER) as research on content-specific science education topics, conducted by scholars with considerable expertise in that content area and most often (though not exclusively) performed *in situ*. This means that the majority of the research is taking place in post-secondary courses, as these are what DBERers are most often teaching. Foremost as the context for astronomy education research (AER) is the general education, introductory astronomy course for nonscience majors, colloquially known as "ASTRO 101." Furthermore, DBERers often share their work through journals and conferences that are of interest to content-area experts (as opposed to education experts). In the case of AER, this includes journals such as *Astronomy Education Review* (which I will abbreviate as *AER** to distinguish it from the general discipline) and *American Journal of Physics* (AJP) and conferences hosted by the American Astronomical Society (AAS), the Astronomical Society of the Pacific (ASP), and the American Association of Physics Teachers (AAPT).

The goals of this review are to present a brief history of the development of astronomy education research and to summarize the research on teaching and learning in astronomy. This paper builds upon previous work by Bailey and Slater (2003) and, in the research summary section, focuses on research that has taken place since that review.

Who Are Astronomy Education Researchers (AERers)?

Prelude: AER is neither PER nor GER

Some might ask why AER – a relatively small field compared to other DBER disciplines – warrants separate attention. It is true that AER is following in the footsteps of physics education research (PER). I believe the primary reason for this is that astronomy faculty are most often housed within physics departments – astronomy-only departments are quite rare. Astronomy faculty within a geosciences department, though also possible, is far less common and tends to occur in smaller schools. Even in institutions in which there is no astronomer, physicists may be asked to teach an ASTRO 101 course. This close connection between physics and astronomy coursework and faculty has led to a close following of PER by AER.

That being said, AER also has some distinct and important differences from PER or geoscience education research (GER) that are worth considering. Non-science majors are more likely to take ASTRO 101 than introductory physics. Furthermore, many ASTRO 101 courses are often taught with little mathematics – unlike introductory physics that, indeed, is often described by the level of mathematics required (e.g., algebra-based versus calculus-based). PER rapidly encompassed many different levels of physics education, and now extends into graduate education in physics. This instructional landscape is very different from that of astronomy, where few institutions even have astronomy majors (Cabanela & Partridge, 2002), and little research is being conducted on higher-level coursework. Astronomy courses may or may not be held with associated laboratory sections, whereas labs are the norm for introductory physics. Finally, AER has benefitted from funding from NASA through its various education and public outreach (E/PO) programs. This is in addition to traditional research funding, such as that provided by the NSF, which supports PER.

What about GER? Whereas there is certainly an overlap of some topics (also true with PER), AER does not really fit there either. Field experiences are an important part of geoscience education, but such experiences are not really within the purview of astronomy (other than experiences with telescopes, perhaps). Astronomy typically is considered part of earth science in K-12, but is more closely associated with physics at the tertiary level (hence, the faculty placement issues as described above). These differences between AER, PER, and GER, in addition to the fields' historical developments as viewed through the researchers involved, support AER as a separate discipline.

AER Trailblazers

When thinking about the origins of AER as a discipline-based field (as opposed to a subset of education research), we can look both at the first doctoral students whose dissertations were based upon AER and at faculty who earned degrees in science fields but later became interested in astronomy education as a research line. Three early doctoral students exemplify the range in time and foci of the early AER dissertations. David Targan earned his Ph.D. from the University of Minnesota in 1988. *The Assimilation and Accommodation of Concepts in Astronomy* (Targan, 1988) investigated ASTRO 101 students' conceptual change about lunar phases, and was guided by faculty from education, physics, and astronomy. Targan is currently an administrator at Brown University and does not appear to be active in AER at this time. Tim Slater's Ph.D. was granted through the Department of Geosciences at the University of South Carolina. Entitled, *The Effectiveness of a Constructivist Epistemological Approach to the Astronomy Education of Elementary and Middle Level In-service Teachers* (T. F. Slater, 1993), this study focused on teachers' changes in knowledge, attitudes, values, and interest after a 15-week astronomy course with a constructivist pedagogical design. Slater's AER career continues to date and will be discussed further below. Rebecca Lindell completed her Ph.D. in 2001 from the University of Nebraska-Lincoln's Department of Physics and Astronomy. *Enhancing College Students' Understanding of Lunar Phases* (Lindell, 2001) included the design of curriculum and an associated assessment instrument for use in ASTRO 101. Lindell's health has limited her continued scholarship in AER in recent years.

Some of the earliest AER faculty at research extensive or intensive universities included (now Emeritus) Professor Michael Zeilik, of the University of New Mexico Department of Physics and Astronomy, and Dr. Jeff Adams and Dr. Greg Francis of the Department of Physics at Montana State University (MSU). Zeilik had received NSF funding as early as 1992 to reform introductory astronomy courses at his institution (Zeilik, 2003). Francis had previously been involved with the University of Washington's PER group and brought that focus to MSU, with occasional forays into AER when working with Adams and Slater. The MSU group formed the Conceptual Astronomy and Physics Education Research (CAPER) Team in 1997, with research foci by faculty and graduate students in both PER and AER. Later, Slater and Adams expanded their work beyond the confines of MSU by collaborating with Zeilik, Lindell, Dr. Beth Hufnagel (Anne Arundel Community College), Dr. Grace Deming (University of Maryland), Ms. Gina Brissenden (then University of Wisconsin-Madison), Christine Brick (then a NSF Post-doctoral Fellow), and others to form the Collaboration for Astronomy Education Research (CAER). The primary accomplishment of CAER was the development of the Astronomy Diagnostic Test (ADT) (Hufnagel et al., 2000), which paved the way for other diagnostic instruments in AER.

Contemporary Scholars and Programs

In 2001, Slater moved to the University of Arizona's Department of Astronomy and reestablished the CAPER Team there, creating one of the first formal programs for graduate students to perform research with a primary focus on issues relating to astronomy education. Led by Slater and supported by

Associate Professor Ed Prather, doctoral students completed coursework in both education and astronomy content, or in some cases entered the program with significant coursework and experience in content but needed the same in education. More than a dozen students were affiliated with the Arizona CAPER Team, most of who could be considered DBERers in their dissertation and subsequent research interests, though the details of their paths may differ. CAPER also welcomed a number of post-doctoral researchers and visiting faculty who were becoming increasingly involved in AER.

Individual scholars are following suit, though whether affiliated with colleges of science or of education varies. Dr. Julia Plummer, Arcadia University, completed her doctorate from the University of Michigan in a self-designed combined program in astronomy and education, with dissertation co-chairs from each college. Dr. Larry Krumenaker earned his doctorate from the University of Georgia's Department of Mathematics and Science Education, having already had considerable expertise in astronomy content through earlier degrees and teaching experience. Montana State's Department of Physics continues its PER program in which some students focus their research on astronomy-related topics; for example, Kathryn Williamson, working under Dr. Shannon Willoughby, is studying issues relating to gravity, thus bridging PER and AER. The University of Colorado at Boulder's Department of Astronomy and Planetary Sciences is following the example of the Department of Physics' strong PER doctoral program; Colin Wallace is a student in the former department studying cosmology education.

Slater (2008) describes what he calls "the first big wave of astronomy education research dissertations" (p.1) that were completed between 2006 and 2008 (several in association with the University of Arizona CAPER Team, and others by individual researchers described above). He claims that these dissertations, in combination with the success of *Astronomy Education Review* and support of DBER by professional societies such as the AAS and the American Physical Society, "clearly signal that astronomy education research is a healthily growing discipline in and of itself" (p. 2). DBER (AER) dissertations now include those listed in Table 1 below. Although many earlier doctoral candidates had looked at astronomy education topics in the past, most research was conducted under the auspices of traditional education programs by students who, in general, did not have significant background in or connections with astronomy.

Table 1. AER dissertations completed in recent years. Degrees were granted by the University of Arizona, except where noted, through a college of education program, but usually with considerable background or coursework in astronomy content. * indicates programs completed in a college of science; ** indicates a joint college of science-college of education program.

Name	Title
David Hudgins (2005) (Univ. of South Africa)	Investigation of the effects of ranking tasks on student understanding of key astronomy topics
Janelle Bailey (2006)	Development of a concept inventory to assess students' understanding and reasoning difficulties about the properties and formation of stars
Erin Bardar* (2006) (Boston Univ.)	Development and analysis of spectroscopic learning tools and the Light and Spectroscopy Concept Inventory for introductory college astronomy
John Keller* (2006)	Part I. Development of a concept inventory addressing students' beliefs and reasoning difficulties regarding the greenhouse effect
Julia Plummer** (2006) (Univ. of Michigan)	Students' development of astronomy concepts across time
Pebble Richwine (2007)	The impact of authentic science inquiry experiences studying variable stars on high school students' knowledge and attitudes about science and astronomy and beliefs regarding the nature of science
Erin Dokter (2008)	"It's the journey": Exploring the consequences of a professional development workshop for college astronomy faculty
Larry Krumenaker (2008) (Univ. of Georgia)	The status and makeup of the U.S. high school astronomy course in the era of No Child Left Behind
Audra Baleisis (2009)	Joining a discourse community: How graduate students learn to speak like astronomers
Erik Brogt (2009)	Pedagogical and curricular thinking of professional astronomers teaching the Hertzsprung-Russell diagram in introductory astronomy courses for non-science majors
Sanlyn Buxner (2010)	Exploring the impact of science research experiences for teachers: Stories of growth and identity
Kendra Sibbernsen (2010) (Cappella Univ.)	The impact of collaborative groups versus individuals in undergraduate inquiry-based astronomy laboratory learning exercises
Stephanie Slater (2010)	The educational function of an astronomy REU program as described by participating women

Slater again moved the CAPER Team, this time to the University of Wyoming in 2008. A new group of doctoral students is continuing to expand the AER community. At the University of Arizona, Prather became director of the Center for Astronomy Education (CAE, originally established in 2003), which offers teaching workshops for astronomy faculty (Brissenden et al., 2007)

But what about faculty who are interested in AER, but who already have their doctorate in astronomy? There are an increasing number of resources that can help astronomers move into AER without going through another degree program. Most recently, Bailey, Slater, and Slater (2011) published a primer on doing AER and have conducted workshops on this topic at AAS and AAPT meetings. The CAE CATS program has led to a collaborative mentorship program for AER-interested (but novice) faculty by more experienced AERers (Brissenden, Impey, Prather, Lee, & Collaboration of Astronomy Teaching Scholars, 2010; Brissenden, Impey, Prather, Lee, & Duncan, 2009). Brogt and colleagues provided an important series of articles that outline ethical and regulatory issues surrounding research involving human subjects (Brogt, Dokter, & Antonellis, 2007; Brogt, Dokter, Antonellis, & Buxner, 2007; Brogt, Foster, Dokter, Buxner, & Antonellis, 2008). Brogt (2007a) also described his own experiences in "becoming a hybrid researcher" who studies both astronomy and astronomy education. These resources serve as informal training opportunities for professional astronomers who have become interested in conducting AER in addition to or instead of traditional scientific research. This again follows the example of PER faculty who created a series of workshops and guiding documents for PER novices (see, for example, http://www.compadre.org/per/per_reviews/volume2.cfm).

A Visual of AERers

One of the challenges in defining DBER is that there is an increasing amount of collaboration between disciplines, making it difficult to demarcate differences. Thus in an attempt to understand "who is doing astronomy-centered DBER," consider Figure 1 below. To create this schematic, I defined "Astronomy Scores" and "Education Scores" for about a dozen people who have been associated with AER. These scores are *loosely* based upon number of degrees in the field (education vs. astronomy or related fields such as physics or geoscience) and research and teaching experience in those same fields. I have further defined three regions on the graph, based in part on my own knowledge of these scholars' research interests, publication venues, and experience. Region 1 comprises what we consider traditional educational research (which might include science education or cognitive science, for example). Science – specifically astronomy, perhaps with some physics – research dominates Region 3. Finally, Region 2 is what we consider the "sweet spot" – these are people who have significant expertise in astronomy and are conducting DBER as defined above. As AER continues to grow, and the experiences of DBERers grow within it, we would expect to see a trajectory toward the upper right of the figure. The research topics and methods used by these researchers are not clearly demarcated, though in general there tends to be a trend toward the topics being relatively more aligned to what the researcher's colleagues and home department would find of interest. (In other words, those researchers whose home is an education college may focus more on topics relating to astronomy in K-12 settings or teacher education, while those in a college of science might be more aligned with our definition of AER with an ASTRO 101 focus.) However, this is in no way limiting or restricted in this regard.

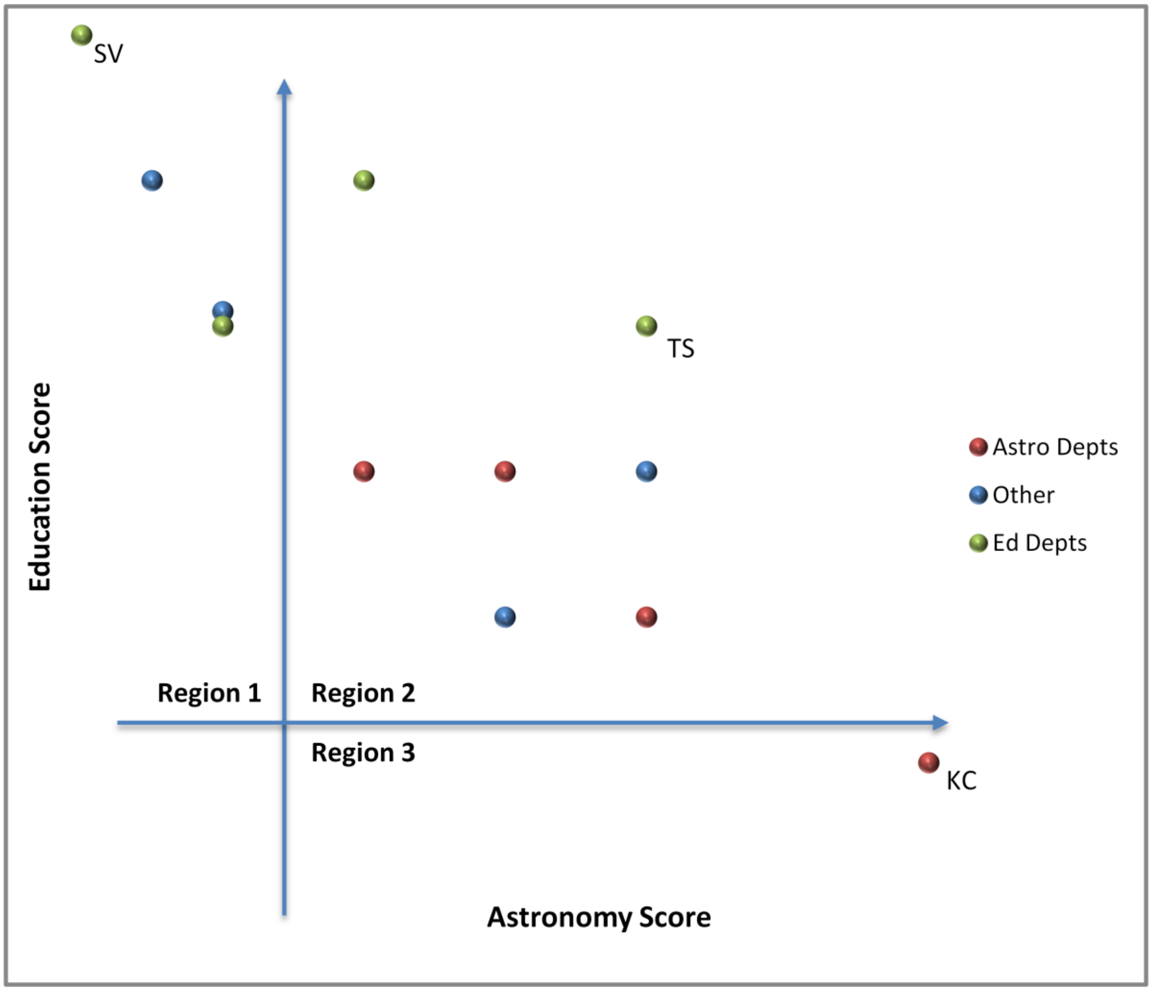

Figure 1. A schematic representation of scholars conducting astronomy education research. Astronomy and education scores are based upon degrees earned plus teaching and research experience in the respective fields. Colors indicate the type of academic home of the current position held by the individual. Regions describe different areas of research focus: (1) traditional education research, (2) AER as defined in this paper, and (3) traditional astronomy research.

Three of the points on are labeled as examples. As a starting point, consider TS, a well-known AERer who has degrees, scholarship, and teaching experiences in astronomy and science education in about equal measure. Contrast his position on Figure 1 with two others. First, on the upper left is SV, a respected and oft-cited cognitive psychologist who frequently investigates children's understanding of astronomical topics, publishing those studies in educational psychology journals, but who has little formal background in astronomy. On the lower right is KC. A respected cosmologist, KC has developed an increasing interest in AER. She is just beginning down this path, and has not yet published research in the field (though she has presented at professional conferences). As she gains this experience in publishing, her Education Score will increase and she will move into Region 2.

Figure 1 is intended to provide a starting point for our discussion and is certainly not comprehensive. Rather, it is an abstraction of the challenge in defining AER as a field because of the wide-ranging expertise brought to bear on understanding astronomy education.

Milestones and the Changing Status of the Field

In most regards, AER is following in the footsteps of PER, with approximately a 20-year lag. The most important milestones have occurred since the late 1990s, and largely in the 21st century. Slater was the first faculty member whose exclusive focus was on AER to earn tenure (2003, Department of Astronomy, University of Arizona), having begun as a research associate professor funded by grants at Montana State University. Prather's path began as a post-doctoral research associate at Montana State, proceeding to an assistant research scientist at Arizona and is expected to earn tenure in Spring 2011.

One area in which AER leapt ahead of PER was in the establishment of a dedicated journal for the field, *Astronomy Education Review* (*AER**), in 2001. Created by Dr. Sidney Wolff (National Optical Astronomy Observatory) and Mr. Andrew Fraknoi (Astronomical Society of the Pacific / Foothills College), and supported by an Editorial Board with a wide range of expertise in astronomy education and public outreach, this electronic journal contains sections entitled Research and Applications, Innovations, Resources, Commentary and News, Reviews and Excerpts, Letters to the Editor, Opportunities, and Extended Thesis/Dissertation Abstracts. *AER** quickly became the primary publishing venue for research on topics of interest to ASTRO 101, though it also includes research at other grade levels, on teacher education, and on informal education. In 2009, AAS took over the responsibility of publishing *AER**. It is supported financially in part by the ASP and the National Science Foundation (NSF), and is hosted on the American Institute of Physics (AIP)'s Scitation platform. Dr. Thomas Hockey (University of Northern Iowa) assumed the role of Editor-in-Chief on January 1, 2010, upon Wolff's retirement from the journal.

A number of other support systems have been established in recent years. These show the value of AER to the broader astronomy research community, in addition to providing support for those engaged in educational research. For example, professional organizations have established committees and published position statements relating to astronomy education and, later, astronomy education research. The AAS created the Astronomy Education Board in 1996, with the new term starting in January 1997 (American Astronomical Society, 2008). AAS also passed a resolution "In Support of Research in Astronomy Education" in 2002 (American Astronomical Society, n.d.) AAPT has an area committee, first known as the Committee on Astronomy Education, which then changed in 2004 to the Committee on Space Science, and Astronomy, which regularly contributes both AER and astronomy content to the organization's meeting programs and wider interests. This committee was first formed in 1983 – significantly earlier than any of these other milestones – specifically with the intent of helping physicists who were tasked with teaching astronomy and astrophysics courses (Dukes, 1990; M. B. Monroe, personal communication, February 14, 2011)

Setting the Stage for Research

Previous Reviews of the Field

Prior to the present work, a number of authors reviewed astronomy education. These tended to be classical literature reviews, providing a reasonable amount of detail on a number of individual studies plus some summary or analysis of trends and gaps in the literature. The earliest I have seen were published in the 1970s (Bishop, 1977; Wall, 1973). Wall found 58 studies published over a 50-year period, and classified them into elementary (K-6), secondary (7-12), and college (13-16 and adult education). Eighteen studies were classified in this last group and included topics such as the need for and training of professional astronomers; issues relating to planetarium education; reports on curriculum development; and the comparison of different instructional strategies. The vast majority of the investigations were performed in association with a graduate degree program, and most were not published after the completion of the thesis or dissertation. Bishop's (1977) review focused on the history of astronomy education, including astronomy coursework in K-12 schools and colleges, rather than on research associated with it.

The 21st century has brought an increased attention to astronomy education research, leading to a number of both broad and focused reviews. Bailey and Slater (2003, 2005) reviewed the status of the field at that time, finding more than 120 studies dating back to 1948. Specific topics or aspects of astronomy education research have also been reviewed in recent years: conceptual change in astronomy (Brewer, 2008); AER in Australia (Broadfoot & Ginns, 2005); gravity (Agan & Sneider, 2004; Kavanagh & Sneider, 2007a, 2007b); lunar phases and eclipses (Albanese, Danhoni Neves, & Vicentini, 1997; Kavanagh, Agan, & Sneider, 2005); and astronomy coursework at the K-12 level (Krumenaker, 2009a, updating work done by Sadler, 1986). Brazell created a meta-analysis on the effectiveness of planetarium instruction when used in a formal education setting (as opposed to an informal education setting, such as with visitors to a science center) (Brazell, 2009; Brazell & Espinoza, 2009). Of the 19 studies included in the meta-analysis, only 4 focused on undergraduate students while the others were at the K-12 level. Most recently, Lelliott and Rollnick (2010) have provided an extensive review of literature published between 1974 and 2008. The authors specifically selected for research that focused on K-12 education and only included post-secondary studies when they related to teacher education. Although comprehensive in this focus, this review ignores the major area of interest for astronomy as a DBER field: the ASTRO 101 course. The SABER database attempts to gather these and other resources into a central location (http://astronomy.uwp.edu/saber/; Bruning, Bailey, & Brissenden, 2007)

Guiding Frameworks

In these and the present reviews, we notice that the majority of AER is situated first in the constructivist framework. “Constructivism… describes knowledge not as truths to be transmitted or discovered, but as emergent, developmental, nonobjective, viable constructed explanations by humans engaged in meaning-making in cultural and social communities of discourse” (Fosnot, 2005, p. ix). This theory is not a prescriptive “how-to” for teaching and learning, but it certainly has implications for the classroom. Many of these are seen in AER – for example, the need to identify alternative conceptions or designing instruction that requires students to be active learners rather than passive listeners both stem from the constructivist theory of learning. Although constructivism is probably the dominant framework in AER, often it is not well documented as such. While it is not clear why this is the case, we might speculate that it relates to the historical lack of theoretical frameworks presented in quantitative education research on which AER may be modeled or to such guiding principles not being explicitly stated as such in astronomy research. It may also be that the number of different interpretations of constructivism (many of which are incomplete or incorrect) may lead researchers to avoid using the term. More attention to the nuances of constructivism as a theoretical framework – or any other framework, for that matter – would serve the community well.

Conceptual change is another theoretical framework commonly employed in AER. As elucidated by Posner, Strike, Hewson, and Gertzog (1982), conceptual change describes the conditions and processes by which learners can move from alternative conceptions to scientific understanding. Posner et al. (1982) modeled the process after Kuhn's (1970) scientific revolutions, which tends to resonate well with the background knowledge of AERers. The field of conceptual change has grown dramatically in the past 30 years, especially through contributions from educational psychology, cognitive science, and science education research that have moved the theory beyond the purely rational process that was implied by Posner et al. (1982) (Pintrich, Marx, & Boyle, 1993; Sinatra, 2005; Vosniadou, 2008b). Reviewing the literature, it appears that the original work by Posner et al. (1982) is still the most common perspective on conceptual change employed in AER to date, with some additional references to ontological categories (Chi, 2005), frameworks or mental models (see, e.g., Vosniadou, 2008a), or knowledge in pieces (see, e.g., diSessa, 2008) sprinkled throughout (Lombardi, Bailey, & Sinatra, 2011).

Finally, while not a formal theoretical framework in the traditional senses, the other common feature of AER is its primary focus on practice (applied research) as opposed to a more theoretical approach. This matches well with our original description of DBER as work done by content experts *in situ*. It is no surprise, then, that the ASTRO 101 course is the most prevalent level studied, with research that can often immediately make an impact in the classroom. This also hints at one of the pathways by which faculty may become interested in AER – action research, or the investigation of one's own situation with the specific goal of improving the learning environment (Bailey, Slater, et al., 2011). Such a focus naturally influences the kinds of questions asked, as will become evident in the summary of the research below. This is one way in which AER lags behind PER and other disciplines, such as cognitive science or science education: the focus has not yet expanded to understanding the underlying cognitive mechanisms that students use to learn astronomy.

Searching for Astronomy Education Research

Because of our previous reviews of AER (Bailey & Slater, 2003, 2005), I had developed an extensive database of articles maintained using the EndNote software package (http://www.endnote.com) to which I have continually added new articles. Thus, my first step in preparing this review was to go through the more than 1,700 entries in this database to determine which might be candidates for inclusion. To consider an article, it should be written by authors involved in AER as described above or focus on astronomy education at the undergraduate level. I also included review papers and articles that I felt may be important for other areas of the paper, such as the Future Directions section.

I next did a broader search of the literature, including searches on ERIC for terms such as "astronomy" and "astronomy education" (plus some topical terms like Sun or Moon). I also reviewed the *AER** website to determine what articles had been published there that might be relevant but were not already in my database. These search methods revealed only a few additional articles. Candidate article abstracts were reviewed and given an initial categorization in preparation for the typology development or were eliminated from this review. Continued reading and analysis of the remaining articles helped me further refine the typologies (described below).

One of the challenges of writing this paper is that although there seems to be a lot of AER going on, much of it remains unpublished and so does not appear in searches such as those described above. In a recent search of the SAO/NASA Astrophysics Data System (ADS), a query of "education" in abstracts for oral or poster presentations at AAS meetings yielded more than 1300 abstracts since 1992; nearly 600 of those were from the year 2006 or later (see

Figure **2**). Notice that the general trend is an increase in the number of abstract submissions over this period. A subsequent search on "ASTRO 101" in all publications included in ADS resulted in a mere 24 hits; 18 of these were abstracts from conference presentations. These search results are illustrative of the nature of AER as a young field, with many research results still in early stages of dissemination and not yet published in refereed journals. This may be congruent with PER, as well as with astronomy research. Conference presentations tend to be more formative in nature, so it should not be surprising that the refereed publications in this rapidly growing field do not yet number as high as meeting contributions. Unfortunately, abstracts provide scant information on the research studies themselves, so if you are not already familiar with the work, it is often difficult to determine whether it makes an important contribution to the field. As such, I have included conference presentation abstracts only where my own knowledge of the work allows me to expand upon the details in a sufficient manner.

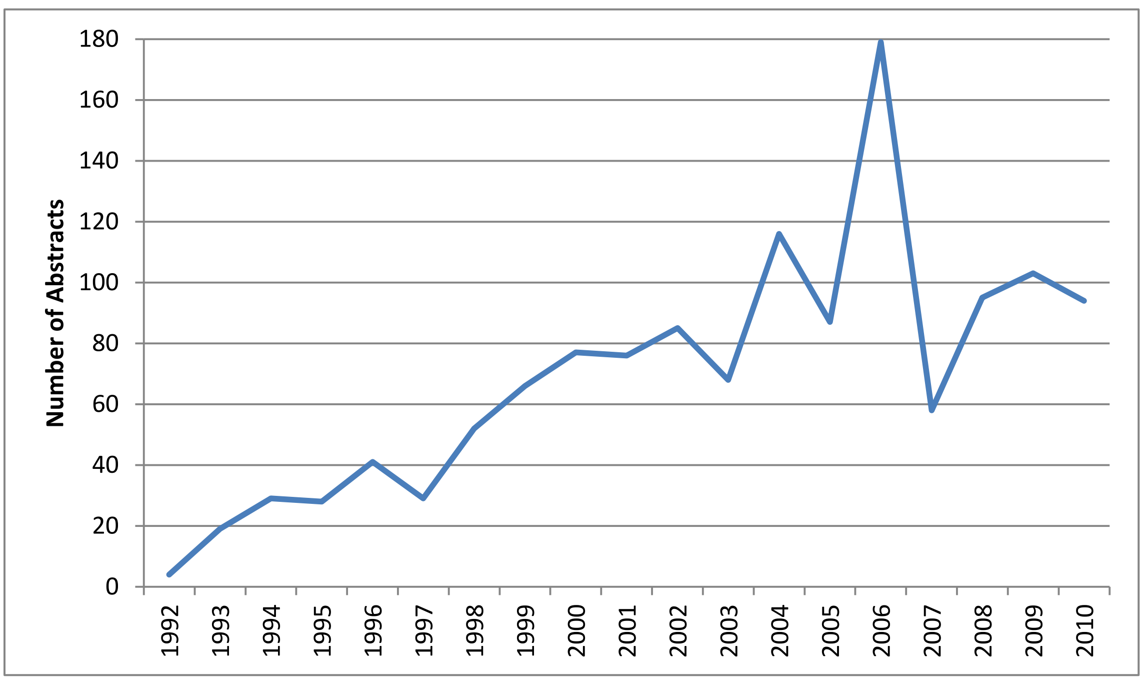

Figure 2. Distribution of hits for an ADS search of AAS abstracts for the word "education." No records were found prior to 1992. I believe the reason for the spike at 2006 is the large number of abstracts from the joint AAS/AAPT meeting held in January 2007, all of which were published in the *Bulletin of the American Astronomical Society* from which the ADS pulls the data. It is not possible to determine which

organization was the "home submission location" based on the information provided through ADS, though my guess based on the tiles would be that only about one-third to one-half of that conference's submissions found in this search would have been through AAS.

A Characterization of Research on the Teaching and Learning of Astronomy

A review of the current state of the field on the teaching and learning of astronomy reveals a number of different categories. Below I will describe six different typologies of AER, which are listed in Table 2. It should be noted, however, that only the first three of these have an appreciable number of published research studies. Typology 4, dealing with high school issues, could have been omitted given the scope and direction of DBER as defined above, but is included because of the nature of the included research studies and the AERers who conducted them. Typology 5 includes graduate students only because the context of one of the studies was a cross-listed course including both them and upper-division undergraduates. Typology 6 is an important prospective area of research and so is included despite its small size.

Table 2. A list of typologies defined in this paper

Typology	Descriptive Title
1	Defining the Problem Areas – Identification of Alternative Conceptions
2	Improving the Classroom – Curricular and Instructional Strategy Effectiveness
3	The Measurement of Ideas – Instrumentation and Assessment
4	Before ASTRO 101 – Relevant Issues from High School Astronomy
5	After ASTRO 101 – Science Majors, Graduate Students, and Upper Division Coursework
6	Beyond Knowledge – Motivation and Interest

Typology 1: Defining the Problem Areas – Identification of Alternative Conceptions

A major result of education research over the past several decades is that students bring with them to classes a number of ideas about the world that can both help and hinder their learning about scientific topics (Donovan & Bransford, 2005). Identifying what those ideas are – and how they can be changed, where needed – was a focus of much education research in the 1980s, and astronomy topics were included. This education research tended to focus on geocentric topics: day/night, seasons, lunar phases, and the like. This is understandable given the nature of astronomy in the K-12 science standards (Adams & Slater, 2000; Palen & Proctor, 2006; T. F. Slater, 2000). However, these topics comprise little – if any – of the ASTRO 101 curriculum, and as such have less direct relevance to the AER researcher or consumer. AERers have instead tended to focus their attention on topics that are of greater importance to the ASTRO 101 course and its instructors. Thus there is still a subset of research focused on the identification of preconceptions on topics such as cosmology (Bailey et al., 2010; Prather, Slater, & Offerdahl, 2002; Wallace, Prather, Duncan, & Collaboration of Astronomy Teaching Scholars, 2010a, 2010b, 2010c), stars (Bailey, Prather, Johnson, & Slater, 2009), astrobiology (Offerdahl, Prather, & Slater, 2002), and planetary orbits (Yu, Sahami, & Denn, 2010).

In this typology, research questions focus primarily on identifying student ideas about given astronomy topics prior to instruction. Such research is grounded in a constructivist framework, and is intended to inform instructors and curriculum designers about typical problem areas that ASTRO 101 students may encounter during their learning. Investigations of student understanding are typically focused on the ASTRO 101 courses (Bailey, et al., 2010; Bailey, et al., 2009; Offerdahl, et al., 2002; Prather, et al., 2002; Wallace, et al., 2010a, 2010b, 2010c; Yu, et al., 2010), although some also consider the ideas of secondary students (Offerdahl, et al., 2002). Most of the ASTRO 101 data were collected at large universities, but some data were also taken from smaller schools or community colleges. These studies generally do not take demographic characteristics, such as gender, race/ethnicity, age, etc. into account.

Data are collected in the form of open-response surveys (Bailey, et al., 2010; Bailey, et al., 2009; Offerdahl, et al., 2002; Prather, et al., 2002; Wallace, et al., 2010a, 2010b, 2010c) and interviews, including drawings (Yu, et al., 2010). Because the nature of these studies is to investigate students' preinstructional ideas, data are usually collected within the first week of class. Data may be collected during a single semester or over several terms, sometimes with question revisions between administrations. Analysis of both open-response and interview data is typically completed through a thematic content analysis (e.g., Stemler, 2001) and/or a grounded theory approach (Charmaz, 2006) where the researchers look for the range of different ideas and pull out common themes. Researchers may also calculate the frequency of observed responses within the different themes. In some cases, responses may be compared to a “correct” or “preferred” response or scored on a rubric in some way.

Because of the varying nature of these research studies, there is a wide range of results. All of these studies show, however, that (a) students have many ideas about these topics, even though they may not have formally studied the topic before; (b) these ideas often contain elements that are correct or scientifically accurate; and (c) ideas may contain incorrect elements or be incomplete in important ways. When multiple grade levels were included in the research, results showed a tendency toward improved understanding at higher grades. A summary of the major findings of this research is included in Table 3.

Table 3. Major results of open-ended surveys and interviews as presented in several studies

Question Topic	**N**	**Major Results**
What is a star?[a]	~400	80% said stars made of gas and dust; responses largely incomplete
Cause of starlight[a]	~1000	32% said burning; 27% chemical reactions; 7% nuclear fusion
How do stars form?[a]	~900	61% said a star is made of gas and dust; 16% indicated gravitational collapse as part of the process
What is the Big Bang?[b,d,e]	~1000	Event that organized preexisting matter (up to 80%); formed the solar system (~33%)
Structure of the universe[b]	~500	Students confuse solar system, galaxy, and universe
Age of the universe[b]	~500	Universe has always existed (~33%); ages provided ranged from 6500 to hundreds of trillions of years
Expansion of the universe[e]	~500	Universe is expanding; expansion increases the distances between stars
Temperature of the universe[e]	~500	Temperature of the universe has remained constant over time
Necessity of sunlight for life[c]	~650	59-78% said life could exist without sunlight; microorganisms and deep underwater creatures were most commonly cited examples
Necessity of water for life[c]	~650	17-27% said life could exist without water; reasons water is essential include: necessary for bodily/cellular function, avoid dehydration, organisms made of water
Implications of temperature on life – can life exist > 100°C or < 0°C[c]	~1450	59-85% said yes, citing microorganisms, desert animals, and Arctic animals as examples; inconsistencies seen (e.g., life can exist in hot but not cold or vice versa)
Limiting environments for life[c]	>1000	Conditions included extreme temperatures (34-42%); no water (19-21%); volcanoes/core of Earth (9-30%); no oxygen/air (16-25%)
Basic elements required for life[c]	~1000	Water (49-61%); oxygen/air (45-56%); energy/nutrients (32-41%); Sun (16-25%)
Description of planetary orbits[f]	~100	70% elliptical or not circular; many indicated high eccentricity of orbits
Speed of planet within its orbit[f]	~100	Fewer than 50% attempted a response; 15% knew planets travel faster when closer to the Sun
Speeds of planets at different distances[f]	~100	>50% said planets move at different speeds, with most knowing inner planets take less time to orbit than outer
Cause of planetary orbits[f]	~100	~33% said the Sun's gravitation pull is the reason that planets stay in orbit

Note: [a]Bailey, et al. (2009); [b]Bailey, et al. (2010); [c]Offerdahl, Prather, and Slater (2002); [d]Prather, et al. (2002); [e]Wallace, et al. (2010a, 2010b, 2010c); [f]Yu, et al. (2010)

Although these studies – and those that came before – have provided great insight into students' ideas, they are not without limitations. Interview studies, which have proven to provide richer detail about students' understanding, are difficult to do in large numbers. Open-response surveys are easier to provide to large numbers of students, but there is typically little detail offered by students and no opportunity to follow up on confusing or interesting responses. It is not clear to what extent research on student conceptions will continue, as the education community increasingly views this area as passé. However, some topics remain relatively untouched (e.g., stellar evolution or galaxies) and may require this fundamental research before other investigations (curriculum development or instrument creation) can take place.

Typology 2: Improving the Classroom – Curricular and Instructional Strategy Effectiveness

The largest area of AER to date focuses on studying the effectiveness of curricular or instructional strategies. Some commonalities in research design and data collection/analysis strategies exist across both of these areas, though there is more consistency within the curriculum development studies than within the instructional strategy effectiveness articles. It should be noted here that there are many other small-scale studies in the instructional strategy category that are not (yet?) published in refereed journals; rather, these reports are appearing as conference presentations or posters (e.g., Jones, Slater, Bailey, Jaeggli, & Lee, 2003; Krok, Cool, Tanner, & Prather, 2010; Krok, Tanner, Cool, & Prather, 2008).

Curriculum Development Effectiveness

Three different curricular materials have been developed and studied in recent years: Lecture-Tutorials (LTs; Prather et al., 2004; Prather, Slater, & Bailey, 2004); ranking tasks (RTs; Hudgins, 2005; Hudgins, Prather, Grayson, & Smits, 2006); and Project LITE (Light Inquiry Through Experiments; Bardar & Brecher, 2008). All three projects were based on the idea that students need to be cognitively engaged with astronomy content more than typically is possible in a lecture setting, and that these materials could supplement (as opposed to replace) traditional lecture. As such, these studies again were situated in a constructivist theoretical framework. The curricular materials were developed with known student difficulties in mind, with strong metacognitive engagement and opportunities for social interactions to support learning.

The LT (Prather, Slater, Adams, et al., 2004; Prather, Slater, & Bailey, 2004) and RT (Hudgins, 2005; Hudgins, et al., 2006) studies both involved a single group, repeated measures research design. In the case of Project LITE (Bardar & Brecher, 2008), a single group used the materials but results were compared to other courses by a common pretest/posttest instrument. All of the included courses were ASTRO 101 from large research institutions and were tested during a single semester. As was the case with Typology 1, none of these studies focused on student demographic characteristics.

All three studies used a multiple-choice instrument administered as a pretest/posttest to investigate student learning gains over the semester as a result of the use of the curricular materials. In the case of the LT and RT studies, instruments were created by selecting relevant questions from other existing instruments and writing new questions where gaps existed (Hudgins, 2005; Hudgins, et al., 2006; Prather, Slater, Adams, et al., 2004; Prather, Slater, & Bailey, 2004). Questions were administered on the first day of class (pretest), with subsets of questions administered after lecture and again after use of the curricular materials. Both of these studies also included an attitudinal survey, and the RT study further collected student responses through open-ended written tasks. Bardar and Brecher (2008) used the Light and Spectroscopy Concept Inventory (LSCI; described below) pretest/posttest as their primary data source.

These studies all showed appreciable gains on the multiple-choice instruments (see Table 4). In the case of Project LITE, LSCI scores increased to a higher level than even with other active engagement strategies such as LTs (see Table 5). The affective survey used in two of the studies showed no significant differences from pretest to posttest on students' attitudes toward astronomy (Prather, Slater, Adams, et al., 2004; Prather, Slater, & Bailey, 2004). In the RT study, specific questions revealed that 83% of the participants believed the RTs contributed positively to their learning of astronomy, and 72% felt the RTs helped in preparation for course exams (Hudgins, 2005; Hudgins, et al., 2006). Because of these results, authors of all three studies felt that their respective curricular materials were effective tools that could be used to improve upon student learning in astronomy above and beyond traditional lecture.

Table 4. Results of learning gains on three curricular materials development studies.

Study	**Pretest Mean**	**Post-Lecture Mean**	**Post-Intervention Mean**
Lecture-Tutorials[a]	30%	52%*	72%[α]
Ranking Tasks[b]	32%	61%*	77%**
Project LITE[c]	24%[d]	n/a	50%[α]

Notes: [a]Prather and colleagues (Prather, Slater, Adams, et al., 2004; Prather, Slater, & Bailey, 2004); [b]Hudgins and colleagues (Hudgins, 2005; Hudgins, et al., 2006); [c]Bardar and Brecher (2008). [d]This pretest mean included all students across multiple courses who took the LSCI, whereas the post-materials mean was for the Project LITE class only. *$p < .05$ when comparing this value to the pretest mean. **$p < .05$ when comparing this value to the post-lecture mean. [α]Results of significance testing were not provided.

Table 5. Mean LSCI scores as reported in Bardar and Brecher (2008), broken down by topic

Topic	**Pretest (ALL)**	**Posttest (Lecture)**	**Posttest (Active Engagement)**	**Posttest (Project LITE)**
Nature of the EM Spectrum	29.3%	51.7%	55.1%	73.3%
Connection between spectral features and physical processes	19.3%	27.7%	32.2%	39.8%
Relationship between blackbody temperature and peak wavelength	24.0%	40.4%	47.4%	51.6%
Interpretation of Doppler shift	22.7%	45.8%	40.7%	57.9%
Relationship between blackbody luminosity, radius, and temperature	28.2%	36.2%	37.5%	39.5%
All LSCI Questions	*24.3%*	*39.1%*	*42.2%*	*50.4%*

Note: Results of significance testing were not reported for these data.

As with all implementation studies, these projects contain a number of different variables that cannot be controlled and may not be adequately addressed through the research design. The researchers took care to maintain consistency wherever possible and to address situations that were beyond their control in their reporting. Another limitation of these studies is in their statistical analyses. Typically, only percentages of knowledge scores are reported (as I have done above). Inferential tests, such as *t*-tests or ANOVAs, may not be used or, if they are used, are not reported in as thorough or robust a manner as is seen in science education or educational psychology research, for example. This means that we may still lack evidence to establish that these materials actually result in meaningful differences above traditional learning. That being said, these studies are still an improvement upon many curriculum development projects of the past, where the materials were described but there was no attempt to evaluate their effectiveness in any systematic way. Furthermore, subsequent studies where these materials were implemented (such as some that will be described in the next section) frequently have used a more robust research design and statistical analyses.

Effectiveness of Active Engagement Strategies

A number of studies have investigated the impact of adding various active engagement strategies into a traditional ASTRO 101 lecture course. The research designs vary somewhat, especially compared to the consistency of the curriculum effectiveness studies, but frequently use a repeated measures design with either a single course, courses over different semesters (i.e., no active engagement in semester 1, strategies added for semester 2), or comparison courses. A summary of several studies published in recent years is provided in Table 6, listed by author in alphabetical order. All of these focus on the ASTRO 101 course or some subset of it (e.g., labs), but the specific active engagement strategies used varies.

Table 6. Summary of results from AER studies on the effectiveness of various active engagement strategies

Study	Study Context	Active Engagement Strategies	Data Collected	Major Results
Alexander (2005)	Conceptual ASTRO 101 vs. mathematical ASTRO 101. Two semesters ($N_1 = 39$, $N_2 = 60$)	Sem. 1: None, traditional lecture. Sem. 2: LTs	• Modified ADT 2.0[a]	• Sem. 1: pretest 32.4%, posttest 47.3%* Effect size (ES) reported as 0.61 (large), method unspecified but probably Cohen's *d*. No significant differences between courses. • Sem. 2: pretest 34.3%, posttest 50.2%* ES 0.93 (very large). No significant differences between courses.
Bailey and Nagamine (2009b)	ASTRO 101 (stars and galaxies only) ($N_1 = 36$, $N_2 = 95$)	Sem. 1: None, traditional lecture. Sem. 2: LTs, Peer Instruction questions	• SPCI[b]	• Sem. 1 (no LTs): 31.2%-49.1%* • Sem. 2 (LTs): 28.7%-60.4%* • No significant difference between pretests • Significant difference between posttests, reported ES (η^2) .106 (moderate)
Cid and Lopez (2010)	Single lab period for ASTRO 101. Two groups. ($N_{2D} = 75$, $N_{3D} = 95$)	2D versus 3D presentation of lab on lunar phases	• LPCI[c]	• 2D mean gain 1.4*, reported ES (r^2) .129 • 3D mean gain 0.905*, reported ES .069 • Both lab types improved but no significant difference between them.
Garland and Ratay (2007)	ASTRO 101 ($N < 20$)	Newspaper, magazine articles (goal to improve science literacy)	• Modified ADT 2.0[a] • Self-created questions	• Improvement on most questions, except where course instruction was not well-aligned with ADT questions • Increases in confidence • Increases in self-assessed science ability • No significance testing or effect size reported
Jacobi et al. (2008)	ASTRO 101 ($N_1 = 82$, $N_2 = 68$)	Nighttime lab sections to accompany traditional lecture	• Self-created questions	• Sem. 1 (no labs) showed gains of 1 to 28% on most of the questions; four questions showed decreases ranging -3 to -26% • Sem. 2 (with labs) showed gains of 4 to 38% on most of the questions; three questions showed decreases ranging -4 to -18% • No significance testing or effect size reported
LoPresto (2010a)	ASTRO 101 ($N \sim 100$)	LTs relating to solar system	• Self-created questions on solar system	• Lecture-only class normalized <g> per question ranged -.115 to .457 • LT class <g> per question ranged .154 to .536 • No significance testing or effect size reported

Study	**Study Context**	**Active Engagement Strategies**	**Data Collected**	**Major Results**
LoPresto and Murrell (2009)	ASTRO 101 (N_{max} = 89)	LTs relating to stars	• SPCI[b]	• Mean pretest 26.9% • Lecture-only posttest 57% • LT posttest 63% • No significance testing or effect size reported
Prather, Rudolph, and Brissenden (2009); Prather, Rudolph, Brissenden, and Schlingman (2009)	69 different ASTRO 101 courses from 31 institutions (N ~4000)	Varied by class, but including none; LTs; RTs; cooperative activities; peer instruction; other	• LSCI[d] • Self-created Interactivity Assessment Instrument	• LSCI can detect variation in posttest results (evidence toward validity) • Classes with > 25% of time using interactive methods, $\langle g_{avg} \rangle = .29$ while classes with < 25% interactivity have $\langle g_{avg} \rangle = .13$* • No effect size reported

Straits and Wilke (2003)	ASTRO 101 (N = 46)	Cooperative activities, up to 4 per class[e]	• ADT 2.0[a]
			• self-created attitude survey
			• interviews (N=26)
			• student evaluation comments
			• researcher observations
				• No significant differences on ADT scores between control and treatment groups (scores not reported)
				• 3 of 24 questions on attitude survey showed significant change ($p < .05$)
				  ○ Significant decrease on self efficacy
				  ○ Decreased (but not significant) in nature of science understanding, attitude toward activity-based instruction, attitude toward science

Notes: [a]Astronomy Diagnostic Test (Hufnagel, 2002; Hufnagel, et al., 2000); [b]Star Properties Concept Inventory (Bailey, 2006, 2007); [c]Lunar Phases Concept Inventory (Lindell, 2001; Lindell & Olsen, 2002); [d]Light and Spectroscopy Concept Inventory (Bardar, 2006; Bardar, Prather, Brecher, & Slater, 2007). [e]Activities taken from Deming, Miller, & Trasco (1997). * $p < .05$

In the 10 studies summarized in Table 6, few attend to students characteristics such as ethnicity, although possible gender differences are sometimes included. Additionally, we frequently observe a lack of robustness in regards to the research design, data collection instruments (i.e., self-created instruments, as opposed to externally validated ones), and particularly in data analysis and reporting. Four of the studies did not report any kind of significance testing (e.g., *t*-tests or ANOVAs), and most of the others report only whether or not the results are significant but do not provide details such as mean scores, *t* or *F* values, or effect sizes (or which method is used to calculate effect size). This makes a direct comparison of the studies, or a formal meta-analysis, difficult if not impossible. If AER is to move forward, more careful analysis and reporting will be required. On the other hand, a veritable smorgasbord of educational research has shown us that deep cognitive engagement is required in order to facilitate meaningful learning, especially conceptual change (see, e.g., Donovan & Bransford, 2005) – so how much AER is required in this arena? It may be that AER is better served by limiting this category of research to studies relating to new and innovative curricular materials or instructional interventions.

Typology 3: The Measurement of Ideas – Instrumentation and Assessment

One of the difficulties in educational research is having the right instrument to measure whatever variable or characteristic that is of interest for your study. It is not surprising, then, that a number of studies have focused on documenting the creation and analysis of validity of standardized assessments. Some of these assessment instruments were used in the studies in Typology 2.

There are two different types of knowledge-based instruments that have been developed within AER. The first is multi-topic instruments. These are often designed to be used as a pretest to the ASTRO 101 course and are therefore based on the astronomy ideas students might be expected to know as a result of their K-12 education. Multi-topic instruments include the Astronomy Diagnostic Test (ADT; Brogt et al., 2007; Hufnagel, 2002; Hufnagel, et al., 2000; Zeilik, 2003), the Astronomy and Space Science Concept Inventory (ASSCI; Sadler et al., 2009), and the Test Of Astronomy STandards (TOAST; Bailey, Slater, et al., 2011; S. J. Slater, 2009; S. J. Slater & Cognition in Astronomy Physics and Earth Science

Research Team, 2009; T. F. Slater & Slater, 2008). These instruments tend to have just one or two questions per topic. The other type is the concept inventory (CI) – an instrument that is focused on a narrowly defined topic or set of related topics, with multiple questions on any given concept (Bailey, 2009). Concept inventories for ASTRO 101 include the Lunar Phases CI (LPCI; Lindell, 2001; Lindell & Olsen, 2002), Star Properties CI (SPCI; Bailey, 2006, 2007), Greenhouse Effect CI (GECI; Keller, 2006), Solar System CI (SSCI; Hornstein, Duncan, & Collaboration of Astronomy Teaching Scholars, 2009; Hornstein et al., 2010), and Light and Spectroscopy CI (LSCI; Bardar, 2006; Bardar, et al., 2007). A concept inventory for cosmology is in early development stages (Cosmology Subject Inventory, or CSI; McLin & Cominsky, 2008). Articles have discussed the need for a CI on a topic of fundamental importance to ASTRO 101 (Bardar, Prather, Brecher, & Slater, 2005), the recommended use of concept inventories (Bailey, 2009), and analysis strategies that go beyond what typically has been used in CI development to date (Wallace & Bailey, 2010).

All of these instruments tend to be distracter-driven, which "force a choice between a single correct answer and one or more misconceptions identified by researchers" (Sadler, et al., 2009, p. 2). These instruments depend upon a robust research base on students' preconceptions, such as that described in Typology 1 and the related K-12 research that came before it. Researchers collected data from hundreds or thousands of students per instrument as part of their validity analysis process. Most have been analyzed via classical test theory methods, though some researchers have instead, or also, employed item response theory (Sadler, et al., 2009; Wallace & Bailey, 2010). Several of these instruments are being used in studies such as in Typology 2, notably the ADT, LSCI, and SPCI (see Table 6). Like in the previous typologies, most of these studies do not investigate variation that may relate to student demographics.

A handful of other studies involve assessment in ASTRO 101 but not instrument development. LoPresto (2010b) combined the use of LTs with visual assessments – completion or analysis of drawings – to determine students' understanding of topics relating to comet orbits, planetary orbits, and extrasolar planets. He used visual tasks as a pretest, a formative (post-lecture) assessment, and summative assessment (after the relevant exam). Such a method would seem to complement the use of sketches in identifying student ideas and reasoning difficulties, such as was used by Offerdahl et al. (2002). Robertson and Finch (2006) report on a 10-year study to look at relationships between "student evaluation data and student-supplied information about sex, race, age, academic background, student study time, study habits, and course grade" (p. 28). The researchers found a number of positive and negative, statistically significant relationships – some of which were hypothesized based upon related education research, while others were unexpected. These studies, and others that have been discussed in earlier reviews, show that discussions of assessment are not limited to instrument development.

Typology 4: Before ASTRO 101 – Relevant Issues from High School Astronomy

With the focus of AER as a DBER field, the research on K-12 education largely has been omitted here and left to be handled by an existing review (Lelliott & Rollnick, 2010). However, high school issues may be relevant to the present paper in two areas. First is a series of papers by Krumenaker. Based upon his dissertation work (Krumenaker, 2008) – itself an update of work done by Sadler in the 1980s – Krumenaker explains the current state of astronomy coursework at the high school level (Krumenaker, 2009a), describes the impact of the *No Child Left Behind* act on high school astronomy (Krumenaker, 2009b), and compares principals' to teachers' perceptions and suggests ways to increase the presence of astronomy in high schools (Krumenaker, 2010).

The second group of papers that are relevant here describe the results of programs in which high school students have used astronomical telescopes or been involved in authentic research. MicroObservatory is a collection of networked robotic telescopes, and the evaluation of 475 student projects, teacher feedback, and student assessments over its first 10 years was the subject of a report by Gould, Dussault, and Sadler (2007). Rosen and colleagues (Rosen et al., 2010) describe the Pulsar Search Collaboratory and their efforts to evaluate the project's effectiveness in its first year. Steinberg, Cormier, and Fernandez (2009) investigate the abilities of students in a summer science program in regards to providing a scientific argument about the relative motion of the Sun and Earth. Finally, Stroud (2008) describes an investigation of the attitudes toward science, science knowledge, and participatory science learning of high school students in a museum internship. Each of these programs showed growth in content knowledge as well as some nature of science and affective variables; however, they are limited to the small numbers of students who have participated in the program and are unlikely to be generalizable to any other program given their highly varied nature. It is possible that further research would show that it is the nature of the program – dealing with authentic experiences, outside of the traditional K-12 classroom stereotype – that makes this difference.

Typology 5: After ASTRO 101 – Science Majors, Graduate Students, and Upper Division Coursework

When we consider AER beyond the ASTRO 101 course, we find only scant research to date. There are few undergraduate astronomy programs in the U.S. (Cabanela & Partridge, 2002), so the available courses in which to conduct research are necessarily limited. Of the five investigations included here, two are yet-unpublished dissertations and relate to different aspects of astronomy career paths, and the other three could have been placed in other typologies if we expanded them beyond ASTRO 101. In the first of the two career-path studies, S. Slater (2010) looked at how women viewed a Research Experiences for Undergraduates (REU) program, and found that it made little difference in their intent to pursue a graduate degree in astronomy. Baleisis (2009) found that although students and faculty had similar goals for having graduate students participate in certain events, in which professional speaking in both informal and formal manners is expected, these goals were frequently unstated and largely unmet.

Two studies with a context beyond ASTRO 101 involved student-understanding research, and as such could have been placed within Typology 1. First, an investigation by Zeilik and Morris (2003) found that science and engineering majors in a two-semester, sophomore-level course sequence made higher gains over their courses than is typically seen with non-science majors, but that they retained a number of misconceptions even after detailed instruction. Gross and Lopez (2009) found, in a small pilot study, that advanced undergraduate and graduate students held misconceptions about the nature of solar wind flow and speculated that the misconceptions may come about as the result of, or be reinforced by, the traditional lecture-based instruction that is typically used in upper-division coursework.

A final study could have been included with Typology 2, although its focus is on graduate students rather than ASTRO 101. Fluke (2008) incorporated virtual field trips, using Google Maps, into an online graduate course on the history of astronomy. In the pilot study, he found that the experience was generally positive and that continuing the use of the virtual field trips may be worthwhile; however, because of the small number of responses, the conclusions should be treated with caution. This study, like several in Typology 2, focused on describing results in a more qualitative fashion rather than incorporating appropriate statistical analyses. Although the number of upper-division and graduate courses in astronomy is small compared to ASTRO 101, this area is ripe for further research.

Typology 6: Beyond Knowledge – Motivation and Interest

Many astronomy instructors state that one of their goals, especially for the ASTRO 101 course, is to increase students' appreciation of or attitudes toward science and especially astronomy (Partridge & Greenstein, 2003; T. F. Slater, Adams, Brissenden, & Duncan, 2001). However, to date not many investigations exist to measure these attitudes. Likewise, other student characteristics that move beyond knowledge – such as their interests, motivations, or self-efficacy for doing astronomy – have rarely been measured by the AER community. Most studies that have touched on these ideas focus on students' reactions to specific instructional strategies or to a change from a traditional lecture course to one that incorporates active engagement strategies.

As part of their instructional effectiveness study, Straits and Wilke (2003) looked at students' response to the changes made in the classroom and found that most characteristics measured by their self-created survey (including attitudes and self-efficacy toward astronomy) remained the same. Wittman (2009) also used a self-created survey, and found slight improvements in his single-course, repeated-measures design. He acknowledges a lack of generalizability of his study, but pointed out that the process of creating the survey helped him solidify what was important to him as the course instructor.

Len (2007) investigated students' use of personal response systems (a.k.a. "clickers") in an ASTRO 101 course and how that use was influenced by two different questions types with associated rewards. Participation was high for both reward types, but the success rate was higher on questions in which students collaborated and there was a bonus offered for correct responses compared to introductory questions for which students only receive participation credit. Prather and Brissenden (2009) looked at the use of clickers not in their typical sense of supporting in-class, collaborative questioning such as in peer instruction, but rather as their effectiveness as a data gathering tool for AER and students' attitudes toward using them. In addition to finding that clickers can be used as a data gathering tool, students felt that the clicker use contributed favorably toward their understanding of class material, achievement on exams, and interest in astronomy topics.

Based on earlier work by Cordova and colleagues (Cordova, Sinatra, Broughton, & Taasoobshirazi, 2010) in educational psychology, Bailey, Lombardi, and Sinatra (2011) investigated the interests in and self-efficacy about topics relating to stars for students enrolled in a sophomore-level astronomy course. They found that both interest and self-efficacy can be maintained over instruction and that students' initial self-efficacy contributes to their learning (as measured by the SPCI) above and beyond their prior knowledge. This investigation is, to the best of my knowledge, the first of its kind in focusing on issues other than knowledge relating to a specific topic of astronomy and using hierarchical multiple regression; this area may also lend itself to future investigations.

Also of Note: Active Areas Outside the Scope of this Review

There are areas of research that are outside of the scope of this review but that may be of interest to AERers. As described above, an extensive review of astronomy education research within the context of K-12 education was recently published (Lelliott & Rollnick, 2010). This review also included research relating to preservice and inservice teacher education in which astronomy is the content of interest. The authors make several conclusions and recommendations: (a) that the identification of conceptions has been sufficiently covered, especially in regards to common K-12 topics such as seasons and lunar phases, and that intervention studies may provide a more valuable line of research; (b) further investigation of how to improve astronomy education for preservice and inservice teachers is warranted; (c) investigators should include the manipulation of physical models as part of their research designs and describe the models and their use fully in their reports; and (d) additional studies relating to the language of astronomy are needed (Lelliott & Rollnick, 2010).

Although Lelliott and Rollnick (2010) included K-12 teacher education in their review, it warrants additional discussion here. Understanding what preservice and inservice teachers know about the astronomy topics they teach has been of interest for a while, and this is still an active area of research within science teacher education (see, e.g., Plummer & Zahm, 2010; Plummer, Zahm, & Rice, 2010; Trumper, 2006; Trundle, Atwood, & Christopher, 2002, 2007). Even before these future teachers get to their education courses in which such studies are taking place, many of them are taking our ASTRO 101 courses (Lawrenz, Huffman, & Appeldoorn, 2005). Thus, any improvements in ASTRO 101 that can result from AER may also assist our future teachers.

Another area of increasing interest is professional development for astronomy faculty. As astronomy instructors embark upon journeys to improve their own teaching, we need to know something about their experiences, the effectiveness of the professional development, and the impact that this has on their classrooms. Recent studies in this area include, for example, case studies of individual faculty (Bailey & Nagamine, 2009a; Brogt, 2007b), the impact on astronomy faculty of professional development workshops (Dokter, 2008), the mentoring of AER scholars (Brissenden, et al., 2010; Brissenden, et al., 2009), and the application of a situated apprenticeship model to professional development (Prather & Brissenden, 2008).

Finally, curriculum development and teaching resources comprise another active area. Materials or supports such as *Lecture-Tutorials for Introductory Astronomy* (Prather, Slater, Adams, Brissenden, & the Conceptual Astronomy and Physics Education Research (CAPER) Team, 2007), *Ranking Tasks for Introductory Astronomy* (Hudgins, et al., 2006), *Peer Instruction for Astronomy* (Green, 2003), and *The Nebraska Astronomy Applet Program* and *Class Action* (Lee, n.d.) are just a few materials that are being developed through research-based methods or are now being used as part of research in the ASTRO 101 realm. Some studies have been completed to ensure the effectiveness of these materials, as described above; however, there are many astronomy activities that have been developed without such research on their quality. Discussions of ASTRO 101 topics (Partridge & Greenstein, 2003; T. F. Slater, et al., 2001; Zeilik & Morris-Dueer, 2005) and pedagogical strategies are also informing curricular materials development. Bruning (2006a, 2006b) provides a survey of astronomy textbooks, and the AstroLrner listserv (T. F. Slater, 2010) is an active discussion forum for a wide variety of issues relating to the ASTRO 101 course.

Future Directions

When reviewing the status of AER as defined here, there are a few recommendations that can be made for future directions. First and foremost relates not to the topic but rather to the research and analysis methods. Robust research designs are generally lacking in this field, especially when compared to educational psychology, science education, and PER. This may be the result of an action research perspective with which many AERers enter the field (T. F. Slater, personal communication, October 17, 2010). In order to stretch this field and not remain behind the rest of the DBER and education research communities, we have to improve this issue. We also need to more carefully present our statistical analyses and expand the methods used. For example, about half of the studies in Typology 2 did not report any statistical significance testing, and those that did generally used *t*-tests only. Results of such tests often have been reported in such a way that they are not easily identified or used in meta-analysis or other comparison studies.

There are also a number of topics that remain uncovered in AER. Three areas in particular stand out here. The first is related to Typology 6. We currently are looking at a very narrow scope of what influences learning – knowledge itself – despite ample evidence from other fields that a person's ability to learn depends on many other things, such as emotions, motivations, and metacognitive skills. Thus, these areas beyond knowledge are open to investigation by AERers. One caution is that to study this topic well, we will need to expand our own knowledge of and work with fields such as cognitive science or educational psychology – if we do not, we will remain in the shadows of research, doomed to repeat other work in an amateur fashion.

The second area where AER could take a lead is in looking at longitudinal and cross-age studies. I know of no AER work that has tracked individual learners over multiple years to determine how their learning changes or what knowledge they retain over time. Working in programs with undergraduate astronomy majors or minors might be a place to start here. A slightly different perspective is taken in the current research on *learning progressions*, for which there are two topics in astronomy currently included. “A learning progression describes one potential pathway between the initial knowledge children first bring to school and the big idea” (Plummer & Krajcik, 2010, p. 768) – it is a model of how students can move from their initial ideas to scientifically accepted knowledge. Researchers are currently developing learning progressions for celestial motion (Plummer & Krajcik, 2010) and seasons (Plummer & Agan, 2010; Willard & Roseman, 2007) but these have so far focused only on K-12 students. The end point is defined by K-12 topics, such as those outlined in Project 2061 or the *National Science Education Standards*, but research has shown repeatedly that ASTRO 101 students often retain difficulties with these topics. As such, it may behoove AERers to join forces with science education researchers to look at how astronomy learning may progress from K-12 to undergraduate settings.

Finally, AER needs to move beyond the identification of what might be considered superficial knowledge and work more toward understanding the underlying cognitive mechanisms that help or hinder students’ learning of astronomy. For example, what role does spatial reasoning play in an ASTRO 101 students’ understanding of topics such as lunar phases, seasons, detection of binary stars and extrasolar planets, or the structure of the universe? How does students’ understanding of scale – in time, distance, and size (mass and volume) – influence their ability to learn astronomy? Further research in areas such as these can push AER into the deeper cognitive mechanisms of learning that so far have been largely untouched in this field.

AER as a branch of discipline-based education research is, in many ways, quite young despite the presence of astronomy topics in education research for several decades. However, it is poised to play a large role in DBER and education research in general. Rather than simply following the path of PER (which, granted, has been a solid and rich one to emulate), we need to look to what unique aspects the ASTRO 101 context in particular can facilitate in our own growth as a field of research. AER has the opportunity to provide insights into learning that may not have yet been addressed in other fields, if only we have the knowledge of what needs to be done, and the courage to do so.

Acknowledgements

I deeply appreciate Tim Slater for suggesting me and Natalie Nielsen for inviting me to participate in this project. Both also provided helpful feedback on the initial draft of this paper and the presentation to the Committee. I would also like to thank Doug Lombardi for the idea and initial design of the figure of AERers, as well as for feedback on this paper.

References

Adams, J. P., & Slater, T. F. (2000). Astronomy in the *National Science Education Standards*. *Journal of Geoscience Education, 48*(1), 39-45.

Agan, L., & Sneider, C. I. (2004). Learning about the earth's shape and gravity: A guide for teachers and curriculum developers. *Astronomy Education Review, 2*(2), 90-117. doi: 10.3847/AER2003017

Albanese, A., Danhoni Neves, M. C., & Vicentini, M. (1997). Models in science and in education: A critical review of research on students' ideas about the earth and its place in the universe. *Science & Education, 6*, 573-590.

Alexander, W. R. (2005). Assessment of teaching approaches in an introductory astronomy college classroom. *Astronomy Education Review, 3*(2), 178-186. doi: 10.3847/AER2004023

American Astronomical Society. (2008). AAS – committees. Retrieved November 18, 2010, from http://members.aas.org/comms/edboard.cfm

American Astronomical Society. (n.d.). Council resolutions. Retrieved November 18, 2010, from http://aas.org/governance/resolutions.php#edresearch

Bailey, J. M. (2006). *Development of a concept inventory to assess students' understanding and reasoning difficulties about the properties and formation of stars.* Ph.D. dissertation, The University of Arizona, Tucson, Arizona. Retrieved from http://proquest.umi.com/pqdweb?did=1068279201&Fmt=7&clientId=17675&RQT=309&VName=PQD

Bailey, J. M. (2007). Development of a concept inventory to assess students' understanding and reasoning difficulties about the properties and formation of stars. *Astronomy Education Review, 6*(2), 133-139. doi: 10.3847/AER2007028

Bailey, J. M. (2009). Concept inventories for ASTRO 101. *The Physics Teacher*, *47*(7), 439-441.

Bailey, J. M., Coble, K. A., Cochran, G., Hayes, V., Larrieu, D., Sanchez, R., et al. (2010). *Using the big ideas in cosmology to teach college students*. Paper presented at the Summer Meeting of the American Association of Physics Teachers, Portland, OR.

Bailey, J. M., Lombardi, D., & Sinatra, G. M. (2011, April). *Investigating college students' self-efficacy, interest, and conceptual change about stars*. Paper accepted for the 84th International Conference of the National Association of Research in Science Teaching, Orlando, FL.

Bailey, J. M., & Nagamine, K. (2009a, August). *Results from a case study investigation on the adoption of learner-centered strategies in introductory astronomy*. Paper presented at the European Association for Research on Learning and Instruction Annual Meeting, Amsterdam, The Netherlands.

Bailey, J. M., & Nagamine, K. (2009b, February). *Using learner-centered strategies to improve student understanding about stars.* Paper presented at the Joint Convention of the 2009 Winter Meeting of the American Association of Physics Teachers and the American Association for the Advancement of Science, Chicago, IL.

Bailey, J. M., Prather, E. E., Johnson, B., & Slater, T. F. (2009). College students' preinstructional ideas about stars and star formation. *Astronomy Education Review*, *8*(1), 010110-010117. doi: 10.3847/AER2009038

Bailey, J. M., Slater, S. J., & Slater, T. F. (2011). *Conducting astronomy education research: A primer*. New York: W.H. Freeman and Company.

Bailey, J. M., & Slater, T. F. (2003). A review of astronomy education research. *Astronomy Education Review, 2*(2), 20-45. doi: 10.3847/AER2003015

Bailey, J. M., & Slater, T. F. (2005). Resource letter AER-1: Astronomy education research. *American Journal of Physics, 73*(8), 677-685.

Baleisis, A. (2009). *Joining a discourse community: How graduate students learn to speak like astronomers.* Ph.D. dissertation, The University of Arizona, Tucson, Arizona. Retrieved from http://proquest.umi.com/pqdweb?did=1788284611&Fmt=7&clientId=17675&RQT=309&VName=PQD

Bardar, E. M. (2006). *Development and analysis of spectroscopic learning tools and the Light and Spectroscopy Concept Inventory for introductory college astronomy*. Ph.D. dissertation, Boston University, Boston, Massachusetts. Retrieved from http://proquest.umi.com/pqdweb?did=1144194241&Fmt=7&clientId=17675&RQT=309&VName=PQD

Bardar, E. M., & Brecher, K. (2008). Project LITE educational materials and their effectiveness as measured by the Light and Spectroscopy Concept Inventory. *Astronomy Education Review, 6*(2), 85-98. doi: 10.3847/AER2007020

Bardar, E. M., Prather, E. E., Brecher, K., & Slater, T. F. (2005). The need for a Light and Spectroscopy Concept Inventory for assessing innovations in introductory astronomy survey courses. *Astronomy Education Review*, *4*(2), 20-27. doi: 10.3847/AER2005018

Bardar, E. M., Prather, E. E., Brecher, K., & Slater, T. F. (2007). Development and validation of the Light and Spectroscopy Concept Inventory. *Astronomy Education Review, 5*(2), 103-113. doi: 10.3847/AER2006020

Bishop, J. E. (1977). United States astronomy education: Past, present, and future. *Science Education, 61*, 295-305.

Brazell, B. D. (2009). *Planetarium instructional efficacy: A research synthesis.* Ed.D. dissertation, Texas A&M University - Commerce, Commerce, Texas. Retrieved from http://proquest.umi.com/pqdweb?did=1793193001&Fmt=7&clientId=17675&RQT=309&VName=PQD

Brazell, B. D., & Espinoza, S. (2009). Meta-analysis of planetarium efficacy research. *Astronomy Education Review, 8*(1), 010108-010111. doi: 10.3847/AER2009033

Brewer, W. F. (2008). Naive theories of observational astronomy: Review, analysis, and theoretical implications. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 155-204). New York: Routledge, Taylor, & Francis Group.

Brissenden, G., Impey, C., Prather, E. E., Lee, K. M., & Collaboration of Astronomy Teaching Scholars. (2010, January). *The Center for Astronomy Education (CAE) and our NSF funded CCLI Phase III Collaboration of Astronomy Teaching Scholars (CATS) program: Updates to our new community-based model for astronomy education research.* Paper presented at the 215th Meeting of the American Astronomical Society, Washington, DC.

Brissenden, G., Impey, C., Prather, E. E., Lee, K. M., & Duncan, D. (2009, January). *The Center for Astronomy Education (CAE) ushers in a new community-based model for astronomy education research with the NSF funded CCLI Phase III Collaboration of Astronomy Teaching Scholars (CATS) program.* Paper presented at the 213th Meeting of the American Astronomical Society, Long Beach, CA.

Brissenden, G., Prather, E. E., Slater, T. F., Greene, W. M., Thaller, M. L., & Alvidrez, R. F. (2008, January). *NASA Center for Astronomy Education: Building a community of practice.* Paper presented at the 211th Meeting of the American Astronomical Society, Austin, TX.

Broadfoot, J., & Ginns, I. (2005). Astronomy education research down under. In J. M. Pasachoff & J. R. Percy (Eds.), *Teaching and learning astronomy: Effective strategies for educators worldwide*. New York: Cambridge University Press.

Brogt, E. (2007a). Astronomy education: Becoming a hybrid researcher. *Journal of Research Practice, 3*(1), article M2. Retrieved from http://jrp.icaap.org/index.php/jrp/article/view/57/82

Brogt, E. (2007b). Instruction as a scientific experiment: A professional development case study of a professor changing the introductory astronomy course for non-science majors. *Astronomy Education Review, 6*(2), 20-31. doi: 10.3847/AER2007016

Brogt, E. (2009). *Pedagogical and curricular thinking of professional astronomers teaching the Hertzsprung-Russell diagram in introductory astronomy courses for non-science majors.* Ph.D. dissertation, The University of Arizona, Tucson, Arizona. Retrieved from http://proquest.umi.com/pqdweb?did=1708324871&Fmt=7&clientId=17675&RQT=309&VName=PQD

Brogt, E., Dokter, E. F., & Antonellis, J. (2007). Regulations and ethical considerations for astronomy education research. *Astronomy Education Review, 6*(1), 43-49. doi: 10.3847/AER2007004

Brogt, E., Dokter, E. F., Antonellis, J., & Buxner, S. (2007). Regulations and ethical considerations for astronomy education research II: Resources and worked examples. *Astronomy Education Review, 6*(2), 99-110. doi: 10.3847/AER2007021

Brogt, E., Foster, T. M., Dokter, E. F., Buxner, S., & Antonellis, J. (2008). Regulations and ethical considerations for astronomy education research III: A suggested code of ethics. *Astronomy Education Review, 7*(2), 57-65. doi: 10.3847/AER2008020

Brogt, E., Sabers, D., Prather, E. E., Deming, G. L., Hufnagel, B., & Slater, T. F. (2007). Analysis of the Astronomy Diagnostic Test. *Astronomy Education Review, 6*(1), 25-42. doi: 10.3847/AER2007003

Bruning, D. (2006a). 2006 survey of introductory astronomy textbooks. *Astronomy Education Review, 4*(2), 54-90. doi: 10.3847/AER2005020

Bruning, D. (2006b). Survey of introductory astronomy textbooks: An update. *Astronomy Education Review, 5*(2), 182-216. doi: 10.3847/AER2006026

Bruning, D., Bailey, J. M., & Brissenden, G. (2007). SABER: The searchable annotated bibliography of education research in astronomy. *Astronomy Education Review, 5*(2), 177-181. doi: 10.3847/AER2006025

Buxner, S. R. (2010). *Exploring the impact of science research experiences for teachers: Stories of growth and identity.* Ph.D. dissertation, The University of Arizona, Tucson, Arizona. Retrieved from http://proquest.umi.com/pqdweb?did=2172831361&Fmt=7&clientId=17675&RQT=309&VName=PQD

Cabanela, J., & Partridge, B. (2002). So what IS the astronomy major? *Astronomy Education Review, 1*(2), 67-84. doi: 10.3847/aer2002007

Charmaz, K. (2006). *Constructing grounded theory: A practical guide through qualitative analysis*. Los Angeles: Sage Publications Ltd.

Chi, M. T. H. (2005). Commonsense conceptions of emergent processes: Why some misconceptions are robust. *Journal of the Learning Sciences, 14*(2), 161-199.

Cid, X. C., & Lopez, R. E. (2010). The impact of stereo display on student understanding of phases of the moon. *Astronomy Education Review, 9*(1), 010105-010107. doi: 10.3847/aer2009044

Cordova, J. R., Sinatra, G. M., Broughton, S. H., & Taasoobshirazi, G. (2010, May). *Self-efficacy, confidence in prior knowledge, and conceptual change.* Paper presented at the Annual Meeting of the American Educational Research Association, Denver, CO.

Deming, G. L., Miller, S. T., & Trasco, J. D. (1997). *Cooperative learning activities in introductory astronomy for non-science majors*. College Park, MD: University of Maryland.

diSessa, A. A. (2008). A bird's-eye view of the "pieces" vs. "coherence" controversy (from the "pieces" side of the fence). In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 35-60). New York: Routledge, Taylor, & Francis Group.

Dokter, E. F. C. (2008). *"It's the journey": Exploring the consequences of a professional development workshop for college astronomy faculty*. Ph.D. dissertation, The University of Arizona, Tucson, Arizona. Retrieved from http://proquest.umi.com/pqdweb?did=1625774361&Fmt=7&clientId=17675&RQT=309&VName=PQD

Donovan, M. S., & Bransford, J. D. (Eds.). (2005). *How students learn: Science in the classroom*. Washington, DC: The National Academies Press.

Dukes, R. J. (1990). Astronomy activities of the American Association of Physics Teachers. In J. M. Pasachoff & J. R. Percy (Eds.), *The teaching of astronomy* (pp. 320-321). New York: Cambridge University Press.

Fluke, C. J. (2008). Virtual field trips: Using Google Maps to support online learning and teaching of the history of astronomy. *Astronomy Education Review, 7*(2), 74-96. doi: 10.3847/AER2008022

Fosnot, C. T. (Ed.). (2005). *Constructivism: Theory, perspectives, and practice* (2nd ed.). New York: Teachers College Press.

Garland, C. A., & Ratay, D. L. (2007). Using literacy techniques to teach astronomy to non-science majors. *Astronomy Education Review, 6*(1), 59-66. doi: 10.3847/aer2007006

Gould, R. R., Dussault, M., & Sadler, P. M. (2007). What's educational about online telescopes? Evaluating 10 years of MicroObservatory. *Astronomy Education Review, 5*(2), 127-145. doi: 10.3847/AER2006022

Green, P. J. (2003). *Peer instruction for astronomy*. Upper Saddle River, NJ: Prentice Hall.

Gross, N. A., & Lopez, R. E. (2009). Advanced undergraduate and early graduate physics students' misconception about solar wind flow: Evidence of students' difficulties in distinguishing paradigms. *Astronomy Education Review, 8*(1), 010102-010109. doi: 10.3847/aer2009013

Hornstein, S. D., Duncan, D., & Collaboration of Astronomy Teaching Scholars. (2009, January). *Development of a Solar System Concept Inventory.* Paper presented at the 213th Meeting of the American Astronomical Society, Long Beach, CA.

Hornstein, S. D., Prather, E. E., English, T. R., Desch, S. M., Keller, J. M., & Collaboration of Astronomy Teaching Scholars. (2010, January). *Continued development of the Solar System Concept Inventory.* Paper presented at the 215th Meeting of the American Astronomical Society, Washington, DC.

Hudgins, D. W. (2005). *Investigation of the effect of ranking tasks on student understanding of key astronomy topics.* Ph.D. dissertation, University of South Africa, South Africa. Retrieved from http://proquest.umi.com/pqdweb?did=1362501511&Fmt=7&clientId=17675&RQT=309&VName=PQD

Hudgins, D. W., Prather, E. E., Grayson, D. J., & Smits, D. P. (2006). Effectiveness of collaborative ranking tasks on student understanding of key astronomy concepts. *Astronomy Education Review, 5*(1). doi: 10.3847/AER2006001

Hufnagel, B. (2002). Development of the Astronomy Diagnostic Test. *Astronomy Education Review, 1*(1), 47-51. doi: 10.3847/AER2001004

Hufnagel, B., Slater, T. F., Deming, G. L., Adams, J. P., Adrien, R. L., Brick, C., et al. (2000). Pre-course results from the Astronomy Diagnostic Test. *Publications of the Astronomical Society of Australia, 17*(2), 152-155.

Jacobi, I. C., Newberg, H. J., Broder, D., Finn, R. A., Milano, A. J., Newberg, L. A., et al. (2008). Effect of night laboratories on learning objectives for a nonmajor astronomy class. *Astronomy Education Review, 7*(2), 66-73. doi: 10.3847/AER2008021

Jones, L. V., Slater, T. F., Bailey, J. M., Jaeggli, S. A., & Lee, A. C. (2003, January). *Astronomy Online: An internet delivered course versus an interactive classroom.* Paper presented at the 126th National Meeting of the American Association of Physics Teachers, Austin, TX.

Kavanagh, C., Agan, L., & Sneider, C. I. (2005). Learning about phases of the moon and eclipses: A guide for teachers and curriculum developers. *Astronomy Education Review, 4*(1), 19-52. doi: 10.3847/AER2005002

Kavanagh, C., & Sneider, C. I. (2007a). Learning about gravity I. Free fall: A guide for teachers and curriculum developers. *Astronomy Education Review, 5*(2). doi: 10.3847/AER2006018

Kavanagh, C., & Sneider, C. I. (2007b). Learning about gravity II. Trajectories and orbits: A guide for teachers and curriculum developers. *Astronomy Education Review, 5*(2), 53-102. doi: 10.3847/AER2006019

Keller, J. M. (2006). *Part I. Development of a concept inventory addressing students' beliefs and reasoning difficulties regarding the greenhouse effect. Part II. Distribution of chlorine measured by the Mars Odyssey Gamma Ray Spectrometer.* Ph.D. dissertation, The University of Arizona, Tucson, Arizona. Retrieved from http://proquest.umi.com/pqdweb?did=1203580221&Fmt=7&clientId=17675&RQT=309&VName=PQD

Krok, M., Cool, A., Tanner, K. D., & Prather, E. E. (2010, January). *The impact of a 5E conceptual change approach to astronomy education.* Paper presented at the 215th Meeting of the American Astronomical Society, Washington, DC.

Krok, M., Tanner, K., Cool, A., & Prather, E. E. (2008, May). *The design and impact of planetarium instruction based on a 5E conceptual change approach to astronomy education.* Paper presented at the 212th Meeting of the American Astronomical Society, St. Louis, MO.

Krumenaker, L. E. (2008). *The status and makeup of the U.S. high school astronomy course in the era of No Child Left Behind.* Ph.D. dissertation, University of Georgia, Athens, GA.

Krumenaker, L. E. (2009a). The modern U.S. high school astronomy course, its status and makeup, and the effects of No Child Left Behind. *Astronomy Education Review, 8*(1), 010107-010108. doi: 10.3847/AER2009052

Krumenaker, L. E. (2009b). No Child Left Behind and high school astronomy. *Science Educator, 18*(2), 10.

Krumenaker, L. E. (2010). What it would take to increase the number of high school astronomy courses: A survey of principals and a comparison to astronomy teachers, and a prescription for change. *Astronomy Education Review, 9*(1), 010102-010109. doi: 10.3847/AER2009076

Kuhn, T. S. (1970). *The structure of scientific revolutions* (2nd ed.). Chicago: The University of Chicago Press.

Lawrenz, F., Huffman, D., & Appeldoorn, K. (2005). Enhancing the instructional environment: Optimal learning in introductory science. *Journal of College Science Teaching, 34*(7), 40-44.

Lee, K. M. (n.d.). UNL astronomy education. Retrieved October 3, 2010, from http://astro.unl.edu/

Lelliott, A., & Rollnick, M. (2010). Big ideas: A review of astronomy education research 1974–2008. *International Journal of Science Education, 32*(13), 1771-1799.

Len, P. M. (2007). Different reward structures to motivate student interaction with electronic response systems in astronomy. *Astronomy Education Review, 5*(2), 5-15. doi: 10.3847/AER2006016

Lindell, R. S. (2001). *Enhancing college students' understanding of lunar phases.* Ph.D. dissertation, The University of Nebraska - Lincoln, Lincoln, Nebraska. Retrieved from http://proquest.umi.com/pqdweb?did=725943501&Fmt=7&clientId=17675&RQT=309&VName=PQD

Lindell, R. S., & Olsen, J. P. (2002, August). *Developing the Lunar Phases Concept Inventory*. Paper presented at the 125th National Meeting of the American Association of Physics Teachers (Physics Education Research Conference), Boise, ID.

Lombardi, D., Bailey, J. M., & Sinatra, G. M. (2011). *Pushing past Posner: Modern theories of conceptual change and their implications for astronomy education*. Manuscript in preparation.

LoPresto, M. C. (2010a). Comparing a lecture with a tutorial in introductory astronomy. *Physics Education, 45*(2), 196-201.

LoPresto, M. C. (2010b). Using visual assessments and tutorials to teach solar system concepts in introductory astronomy. *Astronomy Education Review, 9*(1), 010101-010112. doi: 10.3847/aer2009043

LoPresto, M. C., & Murrell, S. R. (2009). Using the Star Properties Concept Inventory to compare instruction with lecture tutorials to traditional lectures. *Astronomy Education Review, 8*(1), 010105-010105.

Mayer, R. E. (1992). *Thinking, problem solving, cognition* (2nd ed.). New York: W.H. Freeman and Company.

McLin, K. M., & Cominsky, L. R. (2008, January). *Teaching in-service and pre-service teachers modern cosmology, part I: A concept inventory.* Paper presented at the 211th Meeting of the American Astronomical Society, Austin, TX.

Offerdahl, E. G., Prather, E. E., & Slater, T. F. (2002). Students' pre-instructional beliefs and reasoning strategies about astrobiology concepts. *Astronomy Education Review, 1*(2), 5-27. doi: 10.3847/AER2002002

Palen, S., & Proctor, A. (2006). Astronomy in the K-8 core curriculum: A survey of state requirements nationwide. *Astronomy Education Review, 5*(1), 23-35.

Partridge, B., & Greenstein, G. (2003). Goals for "Astro 101": Report on workshops for department leaders. *Astronomy Education Review, 2*(2), 46-89. doi: 10.3847/AER2003016

Pintrich, P. R., Marx, R. W., & Boyle, R. A. (1993). Beyond cold conceptual change: The role of motivational beliefs and classroom contextual factors in the process of conceptual change. *Review of Educational Research, 63*(2), 167-199. doi: 10.3102/00346543063002167

Plummer, J. D. (2006). *Students' development of astronomy concepts across time.* Ph.D. dissertation, University of Michigan, Ann Arbor, Michigan. Retrieved from http://proquest.umi.com/pqdweb?did=1251862001&Fmt=7&clientId=17675&RQT=309&VName=PQD

Plummer, J. D., & Agan, L. (2010, March). *Towards a learning progression addressing the seasons: A comparison of two learning trajectories with middle school students.* Paper presented at the Annual Meeting of the National Association for Research in Science Teaching, Philadelphia, PA.

Plummer, J. D., & Krajcik, J. (2010). Building a learning progression for celestial motion: Elementary levels from an earth-based perspective. *Journal of Research in Science Teaching, 47*(7), 768-787. doi: 10.1002/tea.20355

Plummer, J. D., & Zahm, V. M. (2010). Covering the standards: Astronomy teachers' preparation and beliefs. *Astronomy Education Review, 9*(1), 010110-010128. doi: 10.3847/aer2009077

Plummer, J. D., Zahm, V. M., & Rice, R. (2010). Inquiry and astronomy: Preservice teachers' investigations in celestial motion. *Journal of Science Teacher Education, 21*(4), 471-493.

Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education, 66*(2), 211-227.

Prather, E. E., & Brissenden, G. (2008). Development and application of a situated apprenticeship approach to professional development of astronomy instructors. *Astronomy Education Review, 7*(2), 1-17. doi: 10.3847/AER2008016

Prather, E. E., & Brissenden, G. (2009). Clickers as data gathering tools and students' attitudes, motivations, and beliefs on their use in this application. *Astronomy Education Review, 8*(1), 010103-010110. doi: 10.3847/aer2009004

Prather, E. E., Rudolph, A. L., & Brissenden, G. (2009). Teaching and learning astronomy in the 21st century. *Physics Today, 62*(10), 41-47.

Prather, E. E., Rudolph, A. L., Brissenden, G., & Schlingman, W. M. (2009). A national study assessing the teaching and learning of astronomy. Part I. The effect of interactive instruction. *American Journal of Physics, 77*(4), 320-330. doi: 10.1119/1.3065023

Prather, E. E., Slater, T. F., Adams, J. P., Bailey, J. M., Jones, L. V., & Dostal, J. A. (2004). Research on a lecture-tutorial approach to teaching introductory astronomy for non-science majors. *Astronomy Education Review, 3*(2), 122-136. doi: 10.3847/AER2004019

Prather, E. E., Slater, T. F., Adams, J. P., Brissenden, G., & the Conceptual Astronomy and Physics Education Research (CAPER) Team. (2007). *Lecture-tutorials for introductory astronomy* (2nd ed.). San Francisco: Pearson Addison-Wesley.

Prather, E. E., Slater, T. F., & Bailey, J. M. (2004). Probing the effectiveness of the conventional introductory astronomy lecture. In A. Fraknoi & W. Waller (Eds.), *Cosmos in the classroom 2004: A hands-on symposium on teaching astronomy* (pp. 31-36). San Francisco: Astronomical Society of the Pacific.

Prather, E. E., Slater, T. F., & Offerdahl, E. G. (2002). Hints of a fundamental misconception in cosmology. *Astronomy Education Review, 1*(2), 28-34. doi: 10.3847/AER2002003

Raddick, M. J., Bracey, G., Gay, P. L., Lintott, C. J., Murray, P., Schawinski, K., et al. (2010). Galaxy Zoo: Exploring the motivations of citizen science volunteers. *Astronomy Education Review, 9*(1), 010103-010118. doi: 10.3847/aer2009036

Richwine, P. L. (2007). *The impact of authentic science inquiry experiences studying variable stars on high school students' knowledge and attitudes about science and astronomy and beliefs regarding the nature of science.* Ph.D. dissertation, The University of Arizona, Tucson, Arizona. Retrieved from http://proquest.umi.com/pqdweb?did=1292466561&Fmt=7&clientId=17675&RQT=309&VName=PQD

Robertson, T. H., & Finch, W. H. (2006). Assessment of large general education astronomy classes. *Astronomy Education Review, 4*(2), 28-53. doi: 10.3847/AER2005019

Rosen, R., Heatherly, S., McLaughlin, M. A., Lynch, R., Kondratiev, V. I., Boyles, J. R., et al. (2010). The Pulsar Search Collaboratory. *Astronomy Education Review*, *9*(1), 010106-010113. doi: 10.3847/aer2010004

Sadler, P. M. (1986). Astronomy in U.S. high schools. In J. J. Hunt (Ed.), *GIREP - Cosmos - an educational challenge* (pp. 261-263). Noordwijk, The Netherlands: European Space Agency Publications Division.

Sadler, P. M., Coyle, H., Miller, J. L., Cook-Smith, N., Dussault, M., & Gould, R. R. (2009). The Astronomy and Space Science Concept Inventory: Development and validation of assessment instruments aligned with the K-12 national science standards. *Astronomy Education Review, 8*(1), 010111-010126. doi: 10.3847/AER2009024

Sibbernsen, K. J. (2010). *The impact of collaborative groups versus individuals in undergraduate inquiry-based astronomy laboratory learning exercises.* Ph.D. dissertation, Capella University, Minneapolis, Minnesota. Retrieved from http://proquest.umi.com/pqdweb?did=2031429791&Fmt=7&clientId=17675&RQT=309&VName=PQD

Sinatra, G. M. (2005). The warming trend in conceptual change research: The legacy of Paul R. Pintrich. *Educational Psychologist*, *40*(2), 107-115.

Slater, S. J. (2009, January). *First results from the Test Of Astronomy STandards (TOAST) assessment instrument.* Paper presented at the 213th Meeting of the American Astronomical Society, Long Beach, CA.

Slater, S. J. (2010). *The educational function of an astronomy REU program as described by participating women.* Ph.D. dissertation, The University of Arizona, Tucson, Arizona. Retrieved from http://proquest.umi.com/pqdweb?did=2101583171&Fmt=7&clientId=17675&RQT=309&VName=PQD

Slater, S. J., & Cognition in Astronomy Physics and Earth Science Research Team. (2009, June). *Is it working? Distractor analysis results from the Test Of Astronomy STandards (TOAST) assessment instrument.* Paper presented at the 214th Meeting of the American Astronomical Society, Pasadena, CA.

Slater, T. F. (1993). *The effectiveness of a constructivist epistemological approach to the astronomy education of elementary and middle level in-service teachers.* Ph.D. dissertation, University of South Carolina, Columbia, South Carolina.

Slater, T. F. (2000). K-12 astronomy benchmarks from Project 2061. *The Physics Teacher, 38*(9), 538-540.

Slater, T. F. (2008). The first big wave of astronomy education research dissertations and some directions for future research efforts. *Astronomy Education Review, 7*(1), 1-12. doi: 10.3847/AER2008001

Slater, T. F. (2010). The AstroLrner e-community: A 10 year retrospective. *Astronomy Education Review, 9*(1), 010601-010604. doi: 10.3847/AER2009055

Slater, T. F., Adams, J. P., Brissenden, G., & Duncan, D. (2001). What topics are taught in introductory astronomy courses? *The Physics Teacher, 39*(1), 52-55.

Slater, T. F., & Slater, S. J. (2008, June). *Development of the Test Of Astronomy STandards (TOAST) assessment instrument.* Paper presented at the 212th Meeting of the American Astronomical Society, St. Louis, MO.

Steinberg, R. N., Cormier, S., & Fernandez, A. (2009). Probing student understanding of scientific thinking in the context of introductory astrophysics. *Physical Review Special Topics - Physics Education Research*, *5*, 020104.

Stemler, S. (2001). An overview of content analysis. *Practical Assessment, Research, & Evaluation, 7*(17). Retrieved from http://PAREonline.net/getvn.asp?v=7&n=17

Straits, W. J., & Wilke, R. R. (2003). Activities-based astronomy: An evaluation of an instructor's first attempt and its impact on student characteristics. *Astronomy Education Review, 2*(1), 46-64. doi: 10.3847/AER2003003

Stroud, N. S. (2008). *Teaching and learning science in a museum: Examining the role of attitudes toward science, knowledge of science, and participatory learning in an astronomy internship for high school students.* Ph.D. dissertation, Columbia University, New York, New York. Retrieved from http://proquest.umi.com/pqdweb?did=1553742511&Fmt=7&clientId=17675&RQT=309&VName=PQD

Targan, D. M. (1988). *The assimilation and accommodation of concepts in astronomy*. Ph.D. dissertation, University of Minnesota, Minneapolis, Minnesota.

Trumper, R. (2006). Teaching future teachers basic astronomy concepts - seasonal changes - at a time of reform in science education. *Journal of Research in Science Teaching, 43*(9), 879-906.

Trundle, K. C., Atwood, R. K., & Christopher, J. E. (2002). Preservice elementary teachers' conceptions of moon phases before and after instruction. *Journal of Research in Science Teaching, 39*(7), 633-658.

Trundle, K. C., Atwood, R. K., & Christopher, J. E. (2007). A longitudinal study of conceptual change: Preservice elementary teachers' conceptions of moon phases. *Journal of Research in Science Teaching*, *44*(2), 303-326.

Vosniadou, S. (2008a). Conceptual change research: An introduction. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. xiii-xxviii). New York: Routledge, Taylor, & Francis Group.

Vosniadou, S. (Ed.). (2008b). *International handbook of research on conceptual change*. New York: Routledge, Taylor, & Francis Group.

Wall, C. A. (1973). A review of research related to astronomy education. *School Science and Mathematics*, *73*(8), 653-669.

Wallace, C. S., & Bailey, J. M. (2010). Do concept inventories actually measure anything? *Astronomy Education Review*, *9*(1), 010116. doi: 10.3847/AER2010024

Wallace, C. S., Prather, E. E., Duncan, D., & Collaboration of Astronomy Teaching Scholars. (2010a, January). *Preliminary results on students' reasoning difficulties in cosmology*. Paper presented at the 215th Meeting of the American Astronomical Society, Washington, DC

Wallace, C. S., Prather, E. E., Duncan, D., & Collaboration of Astronomy Teaching Scholars. (2010b, January). *Students' reasoning difficulties in cosmology*. Paper presented at the 215th Meeting of the American Astronomical Society, Washington, DC

Wallace, C. S., Prather, E. E., Duncan, D., & Collaboration of Astronomy Teaching Scholars. (2010c, August). *Understanding and improving students' knowledge of cosmology: The latest results.* Paper presented at the Cosmos in the Classroom 2010, Boulder, CO.

Willard, T., & Roseman, J. E. (2007, July). *Progression of understanding of the reasons for seasons.* Paper presented at the Knowledge Sharing Institute of the Center for Curriculum Materials in Science, Washington, DC.

Wittman, D. (2009). Shaping attitudes toward science in an introductory astronomy course. *The Physics Teacher, 47*(9), 591-594. doi: 10.1119/1.3264591

Yu, K. C., Sahami, K., & Denn, G. (2010). Student ideas about Kepler's laws and planetary orbital motions. *Astronomy Education Review, 9*(1), 010108-010117. doi: 10.3847/aer2009069

Zeilik, M. (2003). Birth of the Astronomy Diagnostic Test: Prototest evolution. *Astronomy Education Review, 1*(2), 46-52. doi: 10.3847/AER2002005

Zeilik, M., & Morris-Dueer, V. J. (2005). What are essential concepts in "Astronomy 101"? A new approach to find concensus from two different samples of instructors. *Astronomy Education Review, 3*(2), 61-108. doi: 10.3847/AER2004017

Zeilik, M., & Morris, V. J. (2003). An examination of misconceptions in an astronomy course for science, mathematics, and engineering majors. *Astronomy Education Review, 2*(1), 101-119. doi: 10.3847/AER2003005

This paper was commissioned for the Committee on the Status, Contributions, and Future Direction of Discipline-Based Education Research. Opinions and statements included in the paper are solely those of the individual author, and are not necessarily adopted or endorsed or verified as accurate by the Board on Science Education or the National Academy of Sciences, including the National Academy of Engineering, Institute of Medicine, or National Research Council.