DEVELOPMENT OF A CONCEPT INVENTORY TO ASSESS
STUDENTS' UNDERSTANDING AND REASONING DIFFICULTIES
ABOUT THE PROPERTIES AND FORMATION OF STARS

by

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To my parents, Kenni and Rick Howard,

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And to my husband, Doug Lombardi,

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ABSTRACT

Stars are one of the most frequently covered topics in introductory astronomy classes. From a constructivist framework, one must know what conceptions students bring with them to the classroom in order to effectively facilitate deep conceptual learning about stars. This study investigated the beliefs about stars that students hold when they enter an introductory astronomy course and used that information to develop a concept inventory that can be used to assess those beliefs pre- and post-instruction.

First, students' pre-instructional beliefs were investigated through the use of student-supplied-response (SSR) surveys, which asked students to describe their ideas about topics such as what is a star, how is starlight created, how are stars formed, are all stars the same, and more. More than 2,200 students participated in this portion of the study over four semesters. Responses were inductively analyzed in an iterative process and coded for themes. Calculated frequencies show that although many students (80%) know that stars are made of gas, a third to half of the participants (32-44%, depending upon the question) believe that starlight is created (or energy otherwise emitted) as a result of the star burning. Nuclear fusion, the true energy source in stars, is identified by fewer than 10% of the students. Interviews with seven volunteers confirmed that the responses seen on the SSR surveys were consistent with verbal explanations.

The second portion of the study involved the design and testing of the Star Properties Concept Inventory. After item development and testing on Versions 1 and 2, interviews with 18 participants about their responses to Version 1, and an expert review

by 26 volunteer astronomy instructors, Version 3 was created and tested during the Fall 2005 semester. Results from approximately 500 students who took Version 3 show that those students in an introductory astronomy course for nonscience majors increased their scores significantly over the semester, whereas a control group (students in an introductory earth science course for nonscience majors) showed no increase. These results support the purpose of this concept inventory to investigate the effectiveness of instruction on the topic of star properties and formation.

CHAPTER 1: INTRODUCTION

Students were once considered *tabula rasa*, “blank slates” on which teachers could simply write new knowledge (Lawson, 1988). The student was assumed to have no prior experiences or ideas that could stand to influence his or her learning. The extreme version of this view is the philosophy of empiricism as described by John Locke, whereby people are born with no prior knowledge; information and events are imprinted upon the brain as they are experienced by the senses (“Tabula rasa,” 2006).

However, this view is no longer the norm in education. The theory of *constructivism* has increasingly been used to explain the process of learning. Summarized by Bodner, constructivism is simply that “knowledge is constructed in the mind of the learner” (1986, p. 873). The idea is that people acquire new knowledge not in isolation, but rather that new information is integrated into their mental landscapes – which have been formed by previous learning experiences. During the 1980’s, constructivism became the dominant theory of educational research in science and mathematics (Osborne, 1993). There are a number of variants of constructivism (e.g., social constructivism, radical constructivism) that exist in the broad arena of educational research (Phillips, 2000), and although constructivism is not universally accepted by all researchers, it has proven to be a useful theoretical basis for the study of students’ understanding.

Research in science education over the last few decades has repeatedly demonstrated, in a variety of contexts, that students have a wide range of ideas, both

scientifically accurate and inaccurate, about the world around them (e.g., Ausubel, 1968; Driver & Easley, 1978; Duit, 2006; McDermott, 1991). Students enter the classroom with tenacious, deep-seated ideas and fundamental reasoning processes that can serve to either help or hinder the incorporation of new concepts. As cognitive science rapidly expands our understanding of how people learn, educators have begun to place more importance on knowing what students understand about a topic when they enter a learning environment.

Humans are viewed as goal-directed agents who actively seek information. They come to formal education with a range of prior knowledge, skills, beliefs, and concepts that significantly influence what they notice about the environment and how they organize and interpret it. This, in turn, affects their abilities to remember, reason, solve problems, and acquire new knowledge.... *If students' initial ideas and beliefs are ignored, the understandings that they develop can be very different from what the teacher intends* [italics added]. (Bransford, Brown, & Cocking, 1999, p. 10)

By approaching teaching and learning from this perspective, educators are encouraged to modify their classes from the traditional teacher-centered model to one which is learner-centered, one which focuses on “the knowledge, skills, attitudes, and beliefs that learners bring to the educational setting” (Bransford, Brown, & Cocking, p. 133). This type of setting has been shown to support more effective and meaningful learning of concepts (e.g., Hake, 1998).

Motivation for the Project

As part of their everyday experiences, individuals have the opportunity to develop ideas about various objects in the sky, such as the Sun and stars. As we look into the sky, we see the brightness of the Sun during the daytime; in the Sun's absence we see thousands of points of light, almost all of which are stars. For thousands of years the appearance of stars has played important roles in the humans' beliefs, including cultural events, religions, timekeeping and calendars, and mythologies.

As our scientific understanding increased, we were able to investigate the Sun and the stars with telescopes and, later, using the techniques of spectroscopy. Through spectroscopic analysis we came to know that the stars and Sun contain the same elements – elements which can also be found on Earth, and were able to determine that the Sun is simply a star that is very close to Earth. Feynman believed – as do many – that this was “the most remarkable discovery in all of astronomy” (Feynman, Leighton, & Sands, 1963, p. 3-6). Astronomers interpret differences in observable properties, such as luminosity, temperature, or mass, to mean that stars exist as different types, and support the theory that those different types of stars imply evolution over time.

Given the importance of stars and star formation in our history and in the evolution of the Universe as a whole, it should come as no surprise that stars are considered one of the central topics in astronomy. In much the same way that the cell is considered the fundamental unit of biology, the star could be considered a fundamental object within the Universe. From a survey of U.S. college syllabi available on the Internet

at that time, Slater, Adams, Brissenden, and Duncan (2001) report that stellar evolution ranked in the top ten most frequent topics covered in an undergraduate introductory astronomy course for nonscience majors (hereafter “ASTRO 101”). Other topics commonly taught include the nature of light, cosmology, our Sun (such as observable characteristics, structure, and energy production), lunar phases, and characteristics of the Milky Way galaxy. Furthermore, because of its prominence in the typical ASTRO 101 course, the teaching effectiveness of this unit is an indication of teaching effectiveness for the course as a whole.

The topic of stars is also deemed important for middle and high school students. “Evolution and Equilibrium” is a unifying concept and process highlighted as an instructional topic for all students in the National Research Council’s *National Science Education Standards* (NSES; NRC, 1996). Because changes over time in natural processes should be addressed through a variety of contexts, the formation and evolution of stars, and their contribution to the evolution of the Universe as a whole, is a topic that supports this aspect of the NSES. Adams and Slater (2000) list 11 NSES content strands where astronomy is either explicitly or implicitly addressed. In the earth science content standards, the history of Earth (grades 5-8) and formation of our solar system (including our star, the Sun; grades 9-12) are both recommended for study. There are several content standards in physical science (grades 9-12 in particular) that the study of stars and stellar evolution supports – “interactions of energy and matter” is perhaps the best example (NRC, 1996). Slater (2000) identifies a total of 27 statements from Project 2061’s *Benchmarks for Science Literacy* (American Association for the Advancement of Science

[AAAS], 1993) that contain astronomy content, and presents them by grade level. Some of these very specifically relate to stars; for example:

By the end of the 12th grade, students should know that...the stars differ from each other in size, temperature, and age, but they appear to be made up of the same elements that are found on the earth and to behave according to the same physical principles. (AAAS, 1993, p. 65)

Since most states' science standards are based upon or influenced by the *Benchmarks*, NSES, or both (Gross et al., 2005; Zucker, Young, & Luczak, 1996), it is reasonable to expect that our ASTRO 101 students might know something about stars at the start of our classes. For some astronomy topics (lunar phases and cosmology, for example), research on student understanding has been conducted and has shown repeatedly that students are not blank slates, but rather have a wide variety of ideas that influence their learning (see, e.g., Abell, Martini, & George, 2001; R. K. Atwood & Atwood, 1996; V. A. Atwood & Atwood, 1995; Lindell, 2001; Nussbaum & Novak, 1976; Offerdahl, Prather, & Slater, 2002; Prather, Slater, & Offerdahl, 2002; Sneider & Pulos, 1983; Vosniadou & Brewer, 1992, 1994). For many other topics, however, including those pertaining to stars, little or no research about students' pre-instructional ideas exists (Bailey & Slater, 2003, 2005).

Scientific Context of the Study

To better understand the scope of the instructional setting in which stars and star formation are covered in the typical ASTRO 101 course, one might look at textbook coverage of the topics. A survey of 23 textbooks investigating the percentage of coverage of these topics shows that, on average, approximately 24% of a book's text (146 pages or

about six chapters) is dedicated to stars; the Sun may be covered here or as part of the 29% of the text (approximately 174 pages) that covers the solar system (Bruning, 2006; see references therein for previous surveys). Table 1 lists a number of subtopics about stars that are discussed in three popular textbooks, as identified through section titles, text boxes, or boldfaced vocabulary words. cursory inspection of other textbooks shows similar coverage. In contrast to the seemingly long list of subtopics, it is important to note that the typical one-semester ASTRO 101 course will likely cover this material in less than two weeks, or fewer than six contact hours with students. (Although some institutions offer two-semester introductory courses, or the option of a more focused semester – such as only the Solar System or a stars and galaxies semester – this project will focus only on the one-semester courses.)

Table 1

Topics Relating to Stars and Star Formation in Three Typical Astronomy Textbooks

Stars	Star Formation
Binary Star Systems	Brown Dwarfs
Evolutionary Tracks	Giant Molecular Clouds
Hertzsprung-Russell (H-R) Diagram	Hydrostatic Equilibrium
Hydrostatic Equilibrium	Interstellar Medium (Gas and Dust)
Luminosity and Apparent Brightness	Nebulae
Luminosity Classes	Nuclear Fusion
Luminosity-Distance Relationship	Star Clusters
Neutrinos	Stellar Disks and Jets
Nuclear Fusion	Stellar Mass
Spectra and Chemical Composition	
Spectral Types	
Stellar Interiors / Layers	
Stellar Lifetimes (Main Sequence Lifetimes)	
Stellar Magnitudes	
Stellar Mass	
Stellar Parallax	
Stellar Radii	
Surface Temperatures and Colors	

Note. From Bennett, Donahue, Schneider, and Voit (2004), Kaufmann and Freedman (1999), and Zeilik (2002). In all three textbooks the first relevant chapter describes properties of stars and how astronomers observe or measure those properties; these topics are reflected in the first column. Star formation (second column) is then covered in its own chapter (Kaufmann III & Freedman; Zeilik) or as the first part of a larger chapter on stellar evolution (Bennett, Donahue, Schneider, & Voit). Items are listed alphabetically and do not necessarily reflect the order of presentation in the textbooks.

Specific coverage of stars in ASTRO 101 courses often focuses first on observable properties, moving later to calculable characteristics and theoretical models. A

definition of a star is not always stated explicitly – for example, only one of the three textbooks used to create Table 1 even includes the term “star” in its glossary. Bennett, Donahue, Schneider, and Voit (2004) define a star as:

A large, glowing ball of gas that generates energy through nuclear fusion in its core. The term *star* is sometimes applied to objects that are in the process of becoming true stars (e.g., protostars) and to the remains of stars that have died (e.g., neutron stars). (p. G-11)

In addition to the basic idea of what a star is, the ASTRO 101 student is typically expected to understand, after instruction, a variety of content relating to the properties of and models used to describe stars. It does not seem unreasonable to assume that many professors would want their students to understand that there are observable differences between stars (such as in apparent brightness, color, or spectrum). Furthermore, these differences can be interpreted to mean that there are related physical variations, some of which support the idea of multiple evolutionary stages. Students might also be expected to learn the relationships between properties; the types of information that can be gleaned from the light we see from stars; the process of nuclear fusion and variations in different stages of stars; or how the distance to a star affects its apparent brightness.

As well as the observable and physical properties of stars described above, there are many details of the process of star formation and evolution that students might be expected to understand after the completion of ASTRO 101. The depth to which this topic is explored varies widely from instructor to instructor, although to a lesser degree in textbook presentation. This research project focuses on the properties and formation of stars, so the details of stellar evolution will not be discussed here.

Description of the Project

If we are to help students overcome the naïve ideas they have about stars and star formation that may interfere with instruction, we must first identify the preexisting concepts they have. This is the purpose of the present study. The project described herein consists of two parts. In Phase I, the nature and range of students' ideas about the properties and formation of stars were investigated. During this first phase of the investigation, more than 2,200 student-supplied-response surveys were collected and seven semi-structured interviews were conducted. In Phase II, a concept inventory, informed by the results of Phase I, was designed, tested, and validated to determine the frequency of students underlying ideas held before and after instruction.

Organization of the Dissertation

Chapter 1 of this dissertation has provided a brief motivation for and description of the dissertation. In chapter 2, a summary of research related to how students' beliefs and reasoning difficulties about stars and star formation is described. Chapter 3 details the methods used in this research project and the results of the study are provided in chapter 4. Finally, chapter 5 describes interpretations of the results and implications for future study.

CHAPTER 2: LITERATURE REVIEW

This chapter will introduce the literature relevant to this research study on the investigation of students' understanding of stars and star formation. As will be shown, very little research on this topic has been conducted to this point. The review starts with an introduction to research on science misconceptions in general, and then moves to literature related to the content addressed in this study.

Research on Student Understanding in Science

Although the beginning of the research movement on student understanding of science concepts is often attributed to Piaget, investigations were made prior to this. As early as the turn of the 20th century, educators reported information about students' ideas about scientific concepts. Hall and Browne (1903) report on the results of questions asked of teachers and normal school students on fire, heat, frost, cold, and related concepts. Huff (1927) tells of investigations of student understanding dating back to 1869, and notes that surprise is always expressed at the "paucity of objects known in nearly every case" (p. 129).

Why surprise should attend the discoveries of such inquiry does not seem to be clear – especially since these percepts are the contact points about which the educational process must develop, and as such are essential knowledges [*sic*] for the teachers to determine. (Huff, p. 129)

Although much of this research has been done with children, other research (especially in the context of physics) has shown that similar ideas are held by college students and teachers as well (Abell, Martini, & George, 2001; Prather, 2000; Prather & Harrington, 2001; Prather, Slater, & Offerdahl, 2002).

As this research movement has increased, a large number of investigations have been conducted. A bibliography of about 7,000 entries relating to students' and teachers' conceptions of all areas of science is maintained by Duit (2006) and is available online. More specific to this study, annotated bibliographies of key research publications have been created for astronomy (Bailey & Slater, 2005) and physics (McDermott & Redish, 1999).

Research on Student Understanding of Content Relating to Stars

Research focusing directly on stars is limited, at best (Bailey & Slater, 2003, 2005). However, research has been conducted on a variety of different concepts that relate to the properties and formation of stars. A review of this literature is presented below, in an order that reflects that which might be encountered in a discussion of star formation.

Matter, the Gaseous State, and Density

Stars form from nebulae, vast regions of space containing primarily gas and some dust. The basic characteristics of this nebular matter, including its state and density, are

fundamental to understanding star properties and formation. Student understanding of matter, state, and density are therefore critical to correct conceptions about stars. In *Making Sense of Secondary Science: Research into Children's Ideas*, Driver, Squires, Rushworth, and Wood-Robinson (1994) summarize research on students' understanding of matter in the gaseous state. The research concludes, for example, that younger students do not have a view of gas as a substance; only as they get older do students begin to recognize that gas has mass and volume. Additionally, the term "gas" often has negative connotations for students, implying, for example, a poisonous or flammable substance.

Children's understanding of density has been assessed through the comparison of the concepts of mass, weight, and density (C. Smith, Maclin, Grosslight, & Davis, 1997). Through interviews and a written test used with eighth-grade students, it was observed that students who understand that "all material objects have weight, no matter how small or light the object, were much more likely to have made a beginning differentiation between weight and density than those who did not" prior to instruction. Most other studies of student understanding of density, which are not relevant to this study, involve students making predictions of buoyancy (see, for example, Kohn, 1993, and references therein). Changes in density over time are rarely encountered at the K-12 level; as a result, students' understanding of this idea has not been investigated.

Gravitational Forces

A key concept in the star formation process is the gravitational attraction between particles that causes them to come together into a smaller, denser region. A number of

studies have investigated students' understanding of gravity, in particular in relationship to the shape of Earth or gravity's effect on falling objects. For example, Stead and Osborne (1981) used interviews with elementary students in New Zealand to investigate their understanding of situations depicted by line drawings; a survey was used afterward to investigate the prevalence of the ideas. Three of the ideas are of particular interest to this study. First, students often believe that gravity requires the presence of air and/or confuse gravity with air pressure. Second, students often consider gravity to be caused by Earth's rotation. Finally, many students believe that gravity does not exist in space (this idea is often associated with the first, that air is necessary for gravity). Similar results have been reported by Watts (1982) in a study with 20 12-17-year-olds. In this case, eight general frameworks were posited as a result of interviews with students (most of these do not relate to this study). Although Watts also observed the "where there's no air, there's no gravity" (p. 118) framework seen by Stead and Osborne, he also suggested that students more generally believed that "gravity is a force that requires a medium to act through" (p. 117).

Halloun and Hestenes (1985a), in their preliminary work on the Mechanics Diagnostic Test (later the Force Concept Inventory, or FCI), report that college students typically defined gravity as "the tendency of objects to fall down" (p. 1064). In a study of secondary students' understanding of static equilibrium, Terry, Jones, and Hurford (1985) observed that students often represented gravity as a force pushing down on an object; drawings were often accompanied by explanations that mirrored other studies' results of air being required for gravity. Smith and Treagust (1988), like previous researchers,

found that students believed gravity to be associated with rotation; they also found that students believed a planet's distance from the Sun affects the strength of its gravitational attraction on an object to the planet. These misunderstandings interfered with the students' abilities to make accurate predictions about what would happen in a fictional solar system.

Agan & Sneider (2004) review several aspects regarding instruction and learning about Earth's shape and gravity. They first look at the historical development of the spherical Earth model and then at what the NSES recommends regarding this topic. The research literature on the topic is reviewed in some detail, with the various articles separated into seminal research expansion research, challenges to prior research, and action research. Finally, recommendations are made to teachers and curriculum developers concerning how to incorporate these research results into their work.

Gravity as a central force, or as an attraction between two objects, is the primary idea relating to this research study, and is not explicitly addressed in any of the aforementioned studies. Research has instead focused on the everyday experiences of students, like objects falling to the ground (e.g., Nussbaum & Novak, 1976; Vosniadou & Brewer, 1992). Personal experience has shown that, in addition to the ideas described above, students often think of gravity as "stuff," a property of an object similar to mass (E. Prather, personal communication, July 28, 2004). As such, they may reason about it in such a way that ignores the idea of "action-at-a-distance" that is critical for understanding the role of gravitational force in star formation.

Temperature

Astronomers, when talking about stars, consider temperature one of the primary properties used to classify stars. The range of temperatures in stars – from a few thousand degrees on the surfaces of the smallest, to hundreds of millions in the cores of the most massive – is well outside the experiences of our everyday lives. It is not surprising, then, that none of the research on student understanding of temperature directly relates to these issues. The research that has been reported frequently combines the ideas of temperature, heat, and thermal conductivity, and reflects those phenomena that students might have direct experience with.

Interviews with 12-year-olds about four tasks relating to heat and temperature reveal a number of ideas that are scientifically incorrect (Erickson, 1979, 1980). Common alternative conceptions include that heat and cold are two different substances with matter-like properties and which can flow like fluids, and that temperature is a measure of how much heat (in the aforementioned substance manner) is contained in an object. Themes similar to those described in these previous studies were found by Erickson and Tiberghien (1985) in children aged 10-16 in several European countries. They found that even though significant gains in understanding can be achieved through instruction, many students retain incorrect or incomplete understandings of heat and temperature.

Other ideas held by students on these topics are summarized by Driver and colleagues (Driver, Guesne, & Tiberghien, 1985; Driver, Squires, Rushworth, & Wood-Robinson, 1994). For example, students often do not make a distinction between heat and temperature, or believe that “heat is hot, but temperature can be cold or hot” (Driver,

Squires, Rushworth, & Wood-Robinson, p. 139). Students have also been found to believe that an object's temperature is related to its size or mass. While none of these ideas were the focus of this study, they are of interest because of the likelihood that students may volunteer inaccurate descriptions of temperature or heat as part of their descriptions of star properties.

Light

The emission of energy in the form of electromagnetic radiation – light – is what allows stars to be observed from Earth. The conversion of mass into energy through nuclear fusion is the primary source of light in stars, although other processes can also produce light. Student understanding of nuclear fusion in stars has not been reported in the literature to date. Instead, most studies have focused on concepts such as the nature of light, color, and vision (C. W. Anderson & Smith, 1986; Feher, 1986; Guesne, 1985; La Rosa, Mayer, Patrizi, & Vicentini-Missoni, 1984; B. F. Stead & Osborne, 1980a, 1980b; Watts, 1985) or concepts in geometric optics (e.g., Galili & Lavrik, 1998; La Rosa, Mayer, Patrizi, & Vicentini-Missoni, 1984). Student understanding of the transmission of light (included in Guesne, 1985; B. F. Stead & Osborne, 1980a, 1980b) is of some interest to this study, as light created in stars must travel through space to Earth in order for the star to be observed, but this concept is of a lower priority than the creation of light.

Like many other studies, Stead and Osborne (1980a, 1980b) only touch on the creation of light, focusing instead on the comparison between making and reflecting light

and the ability of light to travel away from its source. Using interviews of 36 students aged 9-16, Stead & Osborne (1980a) investigated students' understanding of the transmission of light (i.e., that light travels). Interview results were used to develop a multiple-choice test administered to 379 students. With both methods, the authors found that few students consistently held a scientific understanding that light travels until it is reflected or absorbed by an object. The three most common alternative conceptions found in interviews and subsequently used as distracters in the multiple-choice test were that:

- a. light remains at the source,
- b. light travels about a foot away from the source, or
- c. light can travel a meter or more to the observer.

Students' interview responses also indicated that the distance light travels can depend on the size of the source. Results from the multiple-choice test were very similar between those students who had or who had not received instruction on light.

In a case study of a single secondary student, Watts (1985) shows that the participant uses two different descriptions of light, depending upon the context. In some cases, the participant talked about light as being a single entity, perhaps composed of smaller pieces (such as millions of small rays). In other contexts, he described light in different forms, such as sunlight, ultraviolet, electric, and so-on.

Information about students' ideas about light was collected for 10-16 year olds through interviews and surveys by Guesne (1985). A number of aspects of light are addressed; however, none of these involves the *creation* of light. Guesne found that students alternatively viewed light in many different ways: equivalent to its source (e.g., a

lightbulb) or a state of being (e.g., it is light in the room), or as “a distinct entity, located in space” (Guesne, p. 30). She also concluded that the motion of light is not accepted by many children. This may be related to difficulties in understanding large timescales, as propagation is sometimes addressed in relationship to traveling across the vast distances of space. In contrast to Guesne (1985), Anderson and Smith (1986) found that their fifth-grade students did make distinctions between light and its source (such as a lamp or the Sun).

Stead (1980), in an investigation of students’ understanding of energy, found that many children associate energy with living objects (and they note that from previous research, “living” is often associated with motion). At the age of the students’ in question (11-16 years), the conversion of matter into radiative energy, as is the case in nuclear fusion, has probably not been formally addressed. It is therefore unlikely that studies such as Stead’s would garner any information about this aspect of stars or the Sun.

Stars, Including Our Sun

Few studies have been conducted that explicitly target students’ ideas about the Sun or stars, although there have been individual questions on these topics included in studies of a larger focus. Many such studies ask questions that cover the variety of topics that might be included in an ASTRO 101 course. Although their primary focus was students’ ideas of heat and cold, Hall and Browne (1903) report on children’s ideas about the Sun. The research methods and questions are not provided in the article. Children (typically aged 7-8 years) were asked about their ideas of the Sun. Few of the 132

students were able to make a connection between the Sun and either heat or light. Many of their ideas paralleled mythological or religious beliefs of the past (for example, that the Sun dies at night and is reborn the next day, or that it travels to another part of the world when we have night).

In the late 1970's, Schatz and colleagues led workshops that encouraged teaching astronomy under a Piagetian lens, keeping students' developmental progress in mind (Schatz, Fraknoi, Robbins, & Smith, 1978; Schatz & Lawson, 1976). In establishing the need for such considerations, Schatz and Lawson provide two examples of common misconceptions: the "truckin [*sic*] star problem" and "disappearing mass myth" (Schatz & Lawson, 1976, p. 6). The former problem is that students believe a stars' changing position on the H-R diagram to be true spatial motion, when in reality it is a change in one or both of the fundamental properties (temperature and luminosity) displayed by the graph. The latter, where students automatically assume larger diameter stars must have more mass as well, appears to be related to problems with understanding density. No published investigations have been found relating to either of these reported misconceptions, although the anecdotal evidence for them seems generally plausible.

Loria, Michelini, and Mascellani (1986) describe a curriculum unit on the solar system developed for students aged 11-13 in Italian middle schools. In an "Entrance Test," only 25% of the approximately 200 students surveyed recognized that there is a difference between stars and planets. It should be noted here that the actual question was not presented, nor was any information about the test format. It is not clear if this question and subsequent results are based upon visual inspection (i.e., their appearance in

the sky) or upon the intrinsic characteristics of the objects (e.g., the emission versus reflection of light).

Other studies have included one to a few questions relating to stars. Based upon Western Australia's required astronomy curriculum in lower school science (grades 8-10, ages 13-15+), Treagust and Smith (1986) examined students' understanding of the solar system after instruction through interviews and, later, a multiple-choice instrument. The last item in the instrument relates to the Sun's energy and that energy's propagation through space. In the interviews, some students correctly identified that the Sun's energy is created by nuclear fusion while others incorrectly stated that chemical change creates the energy. Proportions of students providing each answer are not given.

The 15-item multiple-choice questionnaire created and administered by Finegold and Pundak (1990) asks several questions that relate to stars. It was administered to 330 students in Years 7 to 12 in Perth, Australia, schools. The purpose of this survey was not to identify specific misconceptions, but rather to assess students' overall framework for thinking about astronomy. The researchers created questions whose distracters could be classified as prescientific, geocentric, heliocentric, or sidereal (aligning with current scientific thought). Perhaps the question from the survey most closely related to this investigation is Question 7. It asks,

What is a star?

- a. A star is a substance which gives light at night.
- b. A star is created from small pieces of material which join up in space.
- c. A star is a place upon which it is possible to live.
- d. A star is a round hot body of material, like the Sun.
- e. A star is a point in the sky which gives out light at night. (1990, p. 82)

The correct answer is not given in the article – though it is assumed to be (d) – and it is not clear how the distracters were chosen. Interestingly, response (b) actually answers a different question (addressing star formation rather than the nature of the object) and was the most attractive distracter at 20%. Results for this question were not discussed in detail, although a figure indicates that approximately 85% of the respondents chose an answer to Question 7 corresponding to a sidereal framework. For question 13 (“Will the Sun always continue to shine?”; p. 83), between 20 and 50% of each grade level chose the correct response. Questions 14 (“What is the difference between a planet and a fixed star?”; p. 83) and 15 (“Star light results from...”; p. 83) elicited a variety of frameworks, with correct responses over the grades ranging approximately 20-45% and 13-28%, respectively.

For the evaluation of Project STAR, Sadler (1992) and colleagues developed a 47-item multiple-choice instrument to investigate students’ misconceptions in astronomy. Questions contained distracters based upon research on student understanding in astronomy or interviews with students, and were written in students’ natural language (i.e., little to no astronomy jargon). The survey was administered to over 1400 students at the start of their astronomy course (grades 8-12). Only one question in Sadler’s instrument addresses issues related to this study. Question 32 asked why two stars of different luminosities might appear to have the same brightness. Forty-four percent of the students answered correctly that the more luminous star must be farther from Earth to appear the same as the less luminous star.

As part of an 18-item, multiple-choice test on earth and space science topics, Schoon (1992) found that two questions elicited possible misconceptions about the cause of moonlight which are related to stars. Of the 1,213 students (elementary, secondary, and adult) surveyed, 16% said that the Moon shines because it is the same as a star, only bigger. Another 10% said the Moon creates light like the Sun. The remaining astronomy questions primarily addressed the Sun's apparent motion across the sky (and its effects) and lunar phases and motion.

In a larger study on astronomy topics included in the National Science Curriculum of the U.K., Sharp (1996) asked 42 10-11-year-olds about their understanding of the Sun and the stars. The majority of students indicated that both the Sun and stars have a "round" shape (although whether or not round clearly meant "spherical" depended upon the question asked). The Sun was described by 67% of the students as "a big/huge ball of fire (gases, flames and heat)"; it was correctly identified by 57% as a star (Sharp, p. 694). Students were not clear on what a star is, although just over half said a star is "like the Sun" (Sharp, p. 697). When asked about the size of stars compared to the Sun, Earth, and Moon, students' responses varied from being smaller than to being larger than these objects, or that stars can have a variety of sizes.

DeLaughter and colleagues investigated college nonscience majors' pre-instructional beliefs about earth science and related topics (DeLaughter, Stein, Stein, & Bain, 1998a, 1998b). Of the 18 open-response items, only one relates directly to this study. Question 7 asks, "How does the Sun generate its energy?" (DeLaughter, Stein, Stein, & Bain, 1998b). Only 9% of the 97 respondents correctly named nuclear fusion as

the process; another 9% said nuclear processes. The most frequent responses were chemical reactions (32%) and “because it is a gas” (18%).

The Astronomy Diagnostic Test (ADT) uses multiple-choice conceptual questions, revised and validated by extensive student interviews, to probe student understanding in a quantitative way. Of the 21 content questions in the ADT, 3 relate directly to this study. Question 8 asks about the source of the Sun’s energy, and Question 17 addresses the relationship between the temperature and color of a star. Question 14 asks about Newton’s Law of Universal Gravitation, which explains how the masses and separation distance of two objects affects the gravitational force between them. Although several articles have been published that describe the ADT’s development (Hufnagel, 2002; Hufnagel et al., 2000; Zeilik, 2003; Zeilik, Schau, & Mattern, 1998) and overall results (Deming & Hufnagel, 2001; Hufnagel et al., 2000; Zeilik, 2003), none present the results of administrations to college nonscience majors broken down by question. Brunsell and Marcks (2005) report the results of each question for a survey of 142 teachers in Wisconsin. The average scores on Questions 8, 17, and 14 were 40%, 57%, and 53%, respectively, with high school teachers scoring consistently higher than middle school and elementary teachers.

As a long-duration example of a study on student understanding, Comins (2000a, 2000b, 2001, n.d.) reports on his requirement that nonscience majors in an introductory astronomy course respond to a different question given at the end of each class meeting. This served the dual purpose of taking attendance within a given class and collecting data for the author over nearly a decade of courses. He eventually compiled common

misconceptions into a short list (Comins, 2000a) and later into a book, *Heavenly Errors* (Comins, 2001). His complete list is maintained on a website (Comins, n.d.) and currently includes more than 1,700 ideas. The website has student ideas divided into several categories. The section on “Stars” contains 227 incorrect ideas, and the “Sun” section has an additional 163 ideas listed. Many of the ideas presented by Comins relate to the present study in varying degrees, too many to be directly listed here. It should also be noted that several of the ideas listed overlap in or even duplicate content, as in the two student statements “thought Sun has the same temperature throughout its volume” and “thought the Sun’s interior is uniform in temperature” (Comins, n.d., “Sun-Temperature” items 8 and 10). Although helpful, this list was neither created from nor analyzed under the auspices of a carefully-designed, systematic research study. As such, the ideas listed warrant further investigation. Careful consideration of individual items suggests that some of the ideas are predominantly factual recall and might simply be correctable with traditional lecture-based methods, while other ideas might require focused and lengthy instructional interventions.

Simonelli and Akerson (2004) asked four astronomy content questions of 37 sixth-grade students. Two of the questions related to issues in this research project: (a) “How do you think our solar system was formed? Explain what you think happened”; and (b) “How is the Sun different from our planet?” (Simonelli & Akerson, pp. 11-12). For the first question, 27% of the respondents said that the solar system was formed through materials coming together. Only one of the responses (3%) mentioned gravity explicitly. Nearly as many (24%) responses suggested that the solar system was formed from the

explosion of a “mega-planet,” and 19% gave explanations that did not describe a process. In answering the second question, participants were able to list a large number of correct facts about the Sun and/or Earth (e.g., Sun is a star, Sun gives off light, Earth reflects light). Of the responses that were incorrect, 22% said that the Sun is on fire or has flames. The same questions were asked of 148 introductory astronomy students (Simonelli & Pilachowski, 2004), although only results for the first question listed above were reported. Similarly to the sixth-graders, 30% of the college students described some kind of accretion process, and 15% mentioned an explosion as part of the process. Additionally, 25% of the responses said that the Big Bang described the formation of the Solar System – a number congruent with a study on cosmology by Prather, Slater, and Offerdahl (2002).

The most comprehensive study to date that directly relates to students’ understanding of stars was performed by Agan (2004). Agan investigated 17 students’ ideas through the use of a clinical interview method. Eight of the students were high school freshmen enrolled in an earth science course and five of the students were undergraduate freshman who had never had an astronomy course. The remaining four students were high school juniors or seniors enrolled in an astronomy course. Interview questions focused on three topic areas: the Sun as a star, the nature of stars, and the distances to stars. None of the earth science students named the Sun when directly asked to identify the closest star to Earth, but their responses to other questions suggested that they knew the Sun to be a star. They had no specific notions of distance or scale related to stars. Three of the five (60%) undergraduate students correctly responded that our Sun

is a star. Some of the undergraduates used more scientific language to describe the nature of stars, and they also had a better sense of scale than the earth science students when asked about stellar distances. The high school astronomy students, however, gave responses which most closely resembled scientific thought in all three topic areas. Agan provides a table of the frequency of responses for all of the primary interview questions.

Despite the existence of literally thousands of articles, books, reports, and conference presentations on students' and teachers' conceptions of science (Duit, 2006), very few relate to the properties or formation of stars. Literature about related topics often reports on young children's ideas, rather than those of college nonscience majors despite that star properties and formation are one of the most common topics in ASTRO 101 (Slater, Adams, Brissenden, & Duncan, 2001). This study addresses a critical deficit in the scholarly literature about college students' conceptions of stars and star formation that is needed for constructivist instructors who want to effectively target students' prior knowledge.

Concept Inventories

Although many of the studies on student understanding of science concepts involve the use of qualitative methods (such as interviews), there are a number of quantitative studies as well. However, a survey of students that covers a wide number of topics is limited in the depth to which students' beliefs can be investigated. One method that has been developed in recent years to address this limitation is the development of

the *concept inventory*. A concept inventory is a multiple-choice instrument which focuses on a narrow concept (or small set of related concepts) and whose distracters are based upon known student difficulties. Concept inventories have been developed, for example, on the topics of force and motion (Halloun & Hestenes, 1985b), lunar phases (Lindell & Olsen, 2002), and natural selection (D. L. Anderson, Fisher, & Norman, 2002).

Research Questions

Although many studies in astronomy have touched on students' understanding of stars, few have addressed the ideas in depth or with large numbers of college nonscience majors. A research project using both quantitative and qualitative methods has been designed to investigate student understanding about star properties and formation. The primary research questions in this study are as follows.

1. Prior to instruction, what do undergraduate nonscience majors who are enrolled in an ASTRO 101 course understand about stars and star formation?
2. How can we use this knowledge to inform the development of a concept inventory to measure student understanding on the topics of stars and star formation, both before and after instruction?
3. Finally, what conceptual difficulties about stars and star formation remain after instruction on these topics, as indicated by comparing students' pre- and post-instructional scores on the concept inventory?

By answering these questions, the astronomy education community can benefit from knowing what kinds of conceptual difficulties to expect from students in an ASTRO 101 course. Furthermore, the concept inventory developed and described in this study provides astronomy instructors with a method of identifying those difficulties, both pre- and post-instruction. This is a critical first step in designing an effective learning environment based upon a constructivist theoretical framework, especially given the dearth of information about this topic in the literature. The methods used to answer these research questions will be described in the next chapter; results will follow in chapter 4.

CHAPTER 3: METHODOLOGY

This mixed-methods research study, conducted over the period Summer 2003 to Spring 2006, sought to investigate student understanding about star properties and formation prior to instruction through the use of open-response surveys and interviews, and then to use those results to inform the development of a concept inventory on the same topics. In this chapter, the setting and participants are first described, followed by descriptions of the methods employed in the two phases of research.

Setting and Participants

This research project was conducted at a large research university in the southwestern United States. Undergraduate enrollments at this institution number more than 28,000 and are approximately 53% female and 47% male. Approximately 65% of the undergraduate students are Caucasian, with another 15% Hispanic. Other ethnicities comprise about 14% of the population, with about 6% unknown. More than two-thirds of the undergraduates are aged 18-21, and the university has a 24% attrition rate after the first year. The university enrolls more than 8,000 students in a variety of professional and graduate programs.

The majority of the participants in this study were undergraduate nonscience majors enrolled in an ASTRO 101 course. Students in this course are typically in their

first year of college and, as is true across the country, frequently are enrolled in the course to satisfy a general education distribution requirement in the natural sciences (Deming & Hufnagel, 2001). At the university in this study, students are expected to take two introductory science courses during their tenure, as well as one sophomore-level natural science course. There are nearly 70 different courses offered by multiple academic departments to address these requirements. The students in these courses are approximately reflective of the university's undergraduate population in terms of gender, age, and ethnicity. A predominantly lecture-based survey course typically serving 100-150 (and in some cases, up to 300) students per section, ASTRO 101 introduces students to a wide range of foundational topics related to observational and theoretical astronomy, using both historical and contemporary contexts as appropriate. Lectures are held in large, auditorium-style classrooms. There is no separate laboratory component to the course at this institution; rather, many instructors incorporate hands-on, group activities into the lecture.

A second group of students participated in this study as a control group. These students were enrolled in a different general education natural science course, on topics other than astronomy. These courses will be called "Earth Science 101" (hereafter "ES 101") for simplicity, as this reasonably describes the majority of the participating sections. The demographic distribution of these courses, in terms of gender, age, class, and ethnicity, is approximately the same as the ASTRO 101 courses.

Design of the Investigation

There were two phases in this research project; each is described in greater detail below. Phase I, conducted over the period Summer 2003 to Fall 2004, was an exploratory study that used student-supplied-response (a.k.a., open-ended) surveys and semi-structured interviews. The intent of Phase I was to investigate the range and frequency of students' beliefs, prior to instruction, about stars and star formation. Student-supplied-response (hereafter "SSR") surveys allow students to express their ideas in their own words, providing as much information as necessary to fully describe their beliefs. Phase II was conducted over the period Spring 2005 to Spring 2006 and involved the creation and testing of a concept inventory that is intended to evaluate any change in students' beliefs after being exposed to different instructional strategies. A timeline of the entire project is provided in Table 2.

Table 2

Timeline of Research Project

Semester	Activity
Phase I: An Exploratory Study on Student Understanding	
Summer 2003	Administer and analyze SSR surveys, Forms ABC
Fall 2003	Administer and analyze SSR surveys, Forms DEF Conduct student interviews and analyze transcripts
Spring 2004	Administer and analyze SSR surveys, Forms GHJK
Summer 2004	Analyze posttest SSR surveys, Forms GHJK
Fall 2004	Administer and analyze SSR surveys, Forms LMN Develop items for Version 1 (a, b, and c) of concept inventory
Phase II: Development and Testing of the Concept Inventory	
Spring 2005	Administer and analyze concept inventory, Versions 1a, 1b, 1c Conduct student interviews and analyze interview transcripts Revise concept inventory to create Version 2 (a and b) Administer concept inventory, Versions 2a, 2b
Summer 2005	Analyze concept inventory data, Versions 2a, 2b Revise concept inventory to create Version 2.5 Expert review of Version 2.5 Analyze expert review data Revise concept inventory to create Version 3
Fall 2005	Administer and analyze concept inventory, Version 3
Spring 2006	Analyze concept inventory data (posttest) Perform validity and reliability analyses Revise concept inventory, if needed

Phase I: An Exploratory Study on Student Understanding

Two different data collection strategies were employed for Phase I of this study; both are described in greater detail below. First, SSR surveys were administered to 2,276 students in 15 sections of the ASTRO 101 course. Second, semi-structured interviews were conducted with seven student volunteers from the same courses. In order to check the reliability of the questions, the data from these two sources were compared during the analysis, as described in chapter 4.

Student-Supplied-Response (SSR) Surveys

A short (1-4 questions) SSR survey was administered to a total of 15 sections of an ASTRO 101 course during the Summer 2003, Fall 2003, Spring 2004, and Fall 2004 semesters. All instructors who were teaching ASTRO 101 each semester were invited via electronic mail to participate in the study. The initial recruitment letters sent to professors each semester are provided in Appendix A. Ten different instructors granted access to their sections for this portion of the study.

Because the purpose of the study was to determine the ideas students hold when they enter ASTRO 101 courses, it was essential that the data were collected prior to any instruction on the topics of interest. Thus, precourse SSR surveys were administered on the first or second day of class in the participating sections. In the final two semesters (Spring 2004 and Fall 2004), SSR surveys were also administered postcourse, during the last two weeks of class. Table 3 summarizes the ASTRO 101 sections, number of students, and SSR survey form for this portion of the study.

Table 3

Number of Respondents by Semester of Administration and Survey Form (Phase I)

		Summer 2003			Fall 2003			Spring 2004				Fall 2004		
	Form	A	B	C	D	E	F	G	H	J	K	L	M	N
PRE	Sections	1	1	1	5	5	5	5	5	5	1	3	3	3
	<i>n</i>	9	8	8	322	332	330	215	214	208	167	153	156	154
POST	Sections	--	--	--	--	--	--	5	5	5	1	3	3	3
	<i>n</i>	--	--	--	--	--	--	111	112	115	139	109	110	108

Note. A dash (--) indicates that the given form was not administered postcourse that semester.

The first questions for the SSR surveys were created to focus on the formation of stars but later were expanded to include other topics such as the creation of light, star properties, and comparisons of stars with other astronomical objects. By using open-ended questions without any preconceived responses on the part of the researcher, participants could provide as much detail as necessary in their responses to express a broad range of ideas. In order to maximize the information gathered from the participating classes, different questions were used to create three or four versions of the survey each semester; these were administered randomly to the participating students. The questions used on all forms are listed in Appendix B.

For the first set of SSR surveys, the topic of interest was star formation. Two questions were created, with only minor wording variations between one another, to investigate these ideas. The questions, “describe where you think stars come from” and “describe how you think a star is formed” became the basis for Forms B and C,

respectively. During development of the questions, it became clear that students needed to also identify what a star is; this question became Form A (“Describe what you think a star is.”)

The administration of the first SSR surveys, Forms A-C, occurred during the Summer 2003 semester, during which a single section of ASTRO 101, comprised of 25 students, participated. By mixing the three forms prior to distribution, approximately equal numbers of each form were randomly disseminated to the participating students. Surveys were completed anonymously; upon collection, each survey form was randomly assigned an identification number. These numbers used a format that included information about the semester completed, course and section, and student. An example of these identification numbers is #033-1029-004.

SSR surveys were inductively analyzed and coded for themes in an iterative process. First, all responses to a given question were read, and common ideas were recorded on separate paper. Because some of the ideas were recorded late in the review process, the surveys were read again to determine whether the emerging themes also appeared in responses earlier in the sequence. This process was repeated until no new themes emerged. Each theme was then assigned a code; matching codes were then written on each completed SSR survey response as appropriate. The frequencies of each code were then tabulated and calculated; results are presented in chapter 4.

After coding the responses for themes, a second level of coding and analysis was performed for some of the questions. In this case, students’ responses were compared to what would be expected as a correct answer at the end of the ASTRO 101 course. These

“correct answers” are not necessarily the ideal response, but rather the *minimum* that instructors might expect their students to know. This choice was made deliberately to minimize differences between individual instructors’ emphases and styles. Elements of the expected correct answer were first identified. Students’ responses were then classified as one of up to five possible categories: Correct (C), containing all elements of the expected correct answer and *no* incorrect statements; Incomplete (I), where the response was missing one or more of the identified elements; Partial (P), where the response contained both incorrect and correct elements; and Wrong (W), where no element of the response matched the identified elements of a correct answer. For some questions an additional category was used: True but insufficient (T), statements that were true but did not address the question in any meaningful way.

For the Fall 2003 semester, changes were made to the SSR surveys based upon the results from the Summer 2003 data. The first change was to allow for the identification of those students who had previously taken an astronomy course (prior to the one in which they were being surveyed). This change was prompted by one of the responses on the first set of surveys: “... I learned this last semester. Before that I didn’t know what the [expletive deleted] a star formed from” (Form B, #032-1021-018). The second set of surveys, Forms D, E, and F, each asked the question, “Have you ever taken an astronomy course **before** the one in which you are in now?”

Additionally, three new content questions (different from those on Forms A, B, and C) were created, one per form. For example, the content question on Form D (hereafter referred to as Form D2, so as to describe the particular question) asked,

“Describe the process by which you think a star is formed. Support your answer with a sketch and labels, if possible.” This is a more formal way of asking about star formation than the questions used on Forms B and C, although the expected (and actual) responses were not significantly different. Participants were also asked to provide a sketch to support their answer, in order to provide another mode of communication that students could use to describe their ideas. Although between 10% and 38% of students, depending upon the question, opted to provide a drawing to support their answer the sketches were not found to give any additional insight into students’ thinking beyond the written responses.

Form E2 asked participants to “list all of the things that you think are present and/or will occur when a star forms.” As before, the design of the question was intended to allow the broadest array of possible student responses. However, this question also served to provide some guidance to students without being too limiting. This particular type of question – where students are asked to list the building blocks and conditions necessary for a particular event or process to occur – had proved useful in previous research (Prather, 2000; Prather, Slater, & Offerdahl, 2002). In the case of Form F2, a completely new question was created to specifically seek out students’ ideas about the light seen from stars. This new question was informed by the results of Form A, when a third of the responses included as part of their definition that stars give off light.

The three new forms (D, E, and F) were randomly distributed to a total of 984 students in five participating sections of ASTRO 101. In the same manner as before, anonymous SSR survey responses were analyzed and coded for themes. Response codes

were tabulated; frequencies of these responses were calculated and are presented in chapter 4.

Questions were once again redesigned for the Spring 2004 semester. Forms G, H, and J were created based upon results from the Fall 2003 surveys and interviews (described in the next section). Each SSR survey again asked about prior astronomy coursework, then asked two content questions (instead of just one, as was the case on Forms A-F), resulting in a total of six different content questions across the three forms. The questions were coupled together in such a way as to not influence the answers to one another, i.e., the paired questions on any given survey intentionally addressed different concepts. Two of these questions (Forms G3 and J3) were variations in wording from the “how we see stars” question on Form F2, so that the student would now focus on how the light from stars is created, rather than how we see it. (In some cases, the more general phrasing had led students to discuss issues such as light traveling over a distance, the use of telescopes to observe stars, or the biological processes involved in human sight.) Questions from Forms A and D, about the definition of a star and about star formation, were repeated onto Forms G2 and H2, respectively, so as to increase the corresponding number of responses.

In addition to these questions from previous surveys, two entirely new questions were created that were based on the result of interviews conducted during Fall 2003 (described in the next section). In these interviews, participants were asked about how stars compare to other objects (specifically, to other stars and to planets). The results of these interview questions, though few in number, suggested that a broader sampling of

the ASTRO 101 population on these topics was warranted. As a result, interview questions were adapted for use on Forms H3 (“Are all stars the same?”) and J2 (“Is there a difference between a star and a planet?”) Both forms also asked participants to expand on their yes/no response by asking students to state the differences or similarities between the objects in question. Forms G, H, and J were randomly distributed to 637 students in five sections of ASTRO 101 on the first day of class of the Spring 2004 semester.

In addition to Forms G, H, and J, a fourth SSR survey form was created for use during Spring 2004. Form K consisted of the same prior astronomy question, plus three of the content questions (paraphrased: what is a star, are all stars the same, and how is stars’ light created). This SSR survey form was completed by 167 students in a sixth section of ASTRO 101 on the first day of class in Spring 2004.

Spring 2004 included an additional change from previous semesters. SSR surveys (Forms G, H, J, and K) were also administered post-instruction, during the last two weeks of class. The purpose of this change was to investigate any change in students’ beliefs that might have resulted from instruction. In all six sections, participants were asked to supply their names on the forms so that the same identification number, initially assigned randomly, could be used on both the precourse and postcourse SSR surveys. Names were removed from the SSRU surveys after the identification numbers were assigned. Because Forms G, H, and J were administered randomly, most participants (approximately 70%) did not receive the same form for the two different administrations. Class-averaged changes for the results of these forms are reported in chapter 4. Matched data were available, however, for the one section of ASTRO 101 whose students all received Form

K. These data were analyzed for both bulk and individual change and are described in chapter 4.

Three additional SSR survey forms were administered during the Fall 2004 semester, with precourse administrations on the first or second day and postcourse surveys administered in the last two weeks of class. Like during the previous semester, each form contained the prior astronomy question plus two content questions. Form L2 again asked about the emission of energy from stars, this time omitting the word “light” to investigate any potential differences from the previous formats of the question. As a result of the responses to the “are all stars the same” question on Forms H3 and K3, two new questions were created. “Why do some stars appear brighter than others?” was used on Form M2, while Form N2 contained a similar question (“Why do some stars appear different colors?”)

The final question on each form (L3, M3, and N3) probed for student understanding about “shooting stars,” a topic which came up in the comparison question (“Are all stars the same?”) on Forms H3 and K3. The object in reality is a meteor, a piece of rock or space debris that has entered Earth’s atmosphere and creates a visible streak of light as it melts; it has nothing directly to do with stars. Form L3 asks, “Other than appearing to move quickly across the sky, how is a *shooting star* different from a *star*?” Forms M3 and N3, however, use a different type of question than the one on Form L3 to investigate students’ ideas about shooting stars. In this case, a hypothetical student statement was provided, and participants were asked to state whether they agreed or disagreed with the hypothetical student’s statement and to explain the reasoning for their

answer. This shooting star question read: “Your friend tells you that a shooting star is the result of a star running out of fuel and ‘burning out.’ Do you agree or disagree with your friend? Explain why you think the statement is correct or incorrect.” This format of question is similar to one used frequently in the astronomy curricular materials, *Lecture-Tutorials for Introductory Astronomy* (Adams, Prather, & Slater, 2002, 2005). The question format allows participants to express their reasoning through a critical analysis of a typical student statement.

Forms L, M, and N were also administered pre- and postcourse during the Fall 2004 semester, to 463 students in three ASTRO 101 sections. In the same manner as before, anonymous SSR survey responses were inductively analyzed and coded for themes. Response codes were tabulated; frequencies of the responses were calculated and are presented in chapter 4.

Student Interviews (Phase I)

The second source of data for Phase I of this study was semi-structured interviews with student volunteers from the ASTRO 101 sections during the Fall 2003 semester. Students were recruited using a “Request for Interview Volunteers (Phase I)” announcement, which is reproduced in Appendix C. The announcement was made in each of the ASTRO 101 sections responding to the SSR surveys; as a result, 19 students volunteered to be interviewed. Appointments for interviews were set up with four of the volunteers during the period September 8-11, 2003 (hereafter referred to as Set 1). These interviews were conducted prior to instruction on stars or star formation (as determined

by the dates and topics given on the syllabi from the students' respective courses).

Interviews lasted between 20 and 45 minutes, depending upon the length of the students' responses.

A set of guided, open-ended questions was designed to elicit students' beliefs about star formation before they received instruction on this topic in their astronomy course (see Appendix D for the interview questions used in Set 1). After first addressing some general questions about their science and astronomy background, students were asked about their understanding of the definition and properties of stars. Participants were also asked to make comparisons between stars and other astronomical objects. Questions were asked about star formation processes and about important associated concepts such as the composition of the star, gravity, and the creation of light. Follow-up questions were asked as needed to probe more deeply or to clarify the student's response.

Transcripts of each interview were inductively analyzed and coded for themes in the same manner as that of the SSR surveys. When themes matched those found in the surveys, this was noted for reference during the development of the concept inventory. A summary of each interview, as well as any drawings made by interview participants, are provided in Appendix E. Results from the interviews are presented in chapter 4.

After the first four interviews, adjustments were made to the interview questions (see Appendix D, Set 2). Questions were added in an attempt to elicit more detailed responses about the nature of stars and the changes stars undergo over their lifetimes. Additionally, students were asked to make comparisons between stars and other objects in order to better elicit their ideas about what a star is. Set 2 interviews were conducted

with an additional three participants during the period September 24-25, 2003. These interviews were transcribed and analyzed in the same manner as used for Set 1, and summaries are presented in Appendix E.

Phase II: Development and Testing of the Concept Inventory

Concept Inventory

The second phase of this research study involved the creation of a concept inventory during Summer and Fall 2004. The concept inventory consisted of 30 multiple-choice questions that made use of Phase I results in the creation of research-based distracters written in students' natural language. The use of multiple-choice questions on a concept inventory allows for the rapid collection of data from a large number of participants; likewise, analysis of the data is expedited by this format. Using research-based distracters helps to ensure that the range of students' ideas is covered in the inventory. Using students' natural language provides a way to investigate students' conceptual understanding, something that might be masked by rote memorization of scientific terminology. Students may use the correct vocabulary but still hold alternative ideas about what that vocabulary means, as has been shown in many studies in physics (e.g., Halloun & Hestenes, 1985b; Prather, 2000; Prather & Harrington, 2001).

Instructors were invited to participate in a fashion similar to that of Phase I (see Appendix F). Data were collected over two semesters, Spring and Fall 2005. In addition to the ASTRO 101 courses, several ES 101 courses were recruited to serve as a control group (these letters are also reproduced in Appendix F). A total of 15 instructors provided

access to their courses, with a total of 16 sections and approximately 2,100 students. Table 4 summarizes the ASTRO 101 and ES 101 sections and number of students participating in this portion of the study. In addition to the 30 content questions, students were asked three other questions. The first (Question 31) served as the initial recruitment for interviews that would be conducted later in the semester. Question 32 asked the students' gender, in order to identify whether results differed between female and male participants. Finally, Question 33 asked whether the student had taken a previous astronomy course. No other demographic questions (e.g., ethnicity, prior physics or mathematics coursework) were asked because they were beyond the scope of this study.

Table 4

Number of Respondents by Semester of Administration and Class (Phase II)

		Spring 2005		Fall 2005	
	Classes	ASTRO 101	ES 101	ASTRO 101	ES 101
PRE	Sections	6	2	5	3
	<i>n</i>	796	169	690	411
POST	Sections	6	1	5	2
	<i>n</i>	469	76	489	155

During Spring 2005, Version 1 of the instrument was administered in three different formats (see Appendix G). In Version 1a, the questions were presented in a multiple-choice format. In Version 1b, a subset of the multiple-choice questions was given and respondents were additionally asked to explain the reasoning behind their

choice. Finally, Version 1c used only the stem of the multiple-choice question (i.e., no distracters were provided) and respondents were asked to provide short answers with explanations. An example of one question from each of the three different formats is presented in Table 5. The three formats were randomly administered to eight sections of general education natural science courses on the first day of class. Six sections were of ASTRO 101, and two sections were of ES 101. The ES 101 courses served as a formal control group for the analysis because one would not anticipate they would have formal instruction about stars or star formation during the semester. Nearly 1,100 students were involved in this portion of the study. Names were again collected on the responses for the purpose of matching data in the post-course administration, but were dissociated from the surveys after identification numbers had been randomly assigned.

Table 5

Example Questions from Different Formats of Version 1 of the Concept Inventory

Form	Example Question
Version 1a	<p>Compared to the Sun, the greatest energy output (brightness) a star will ever have is</p> <ul style="list-style-type: none"> a. 10 – 100 times greater b. 100 – 1,000 times greater c. 1,000 – 10,000 times greater d. 10,000 – 100,000 times greater e. more than 100,000 times greater
Version 1b	<p>Compared to the Sun, the greatest energy output (brightness) a star will ever have is</p> <ul style="list-style-type: none"> a. 10 – 100 times greater b. 100 – 1,000 times greater c. 1,000 – 10,000 times greater d. 10,000 – 100,000 times greater e. more than 100,000 times greater <p>Explain the reasoning behind the choice you made.</p>
Version 1c	<p>Compared to the Sun, the greatest energy output (brightness) a star will ever have is how many times greater or smaller?</p>

The purpose of the three formats was to investigate the reliability and validity of the distracters produced. Interviews (described in the next section) served to determine the internal consistency of the instrument by determining if students interpreted the concept inventory questions in the same way at different times. Analysis of these data included inductively analyzing the open-ended responses (Version 1c) and comparing the results to those in the multiple choice format (Versions 1a and 1b).

Upon analyzing the results of Version 1 and the interviews (described in the next section), changes were made to some of the questions on the concept inventory and

Version 2 was created. Eleven of the 30 content questions remained unaltered for Version 2 except for the correction of minor typographical errors. Three questions were rewritten to compare the Sun to other stars on particular intrinsic properties, while another question was rewritten to address intrinsic properties of stars rather than their potential motions.

The stem or at least one distracter was changed on 13 questions to better represent students' ideas and language, as determined from Version 1c or student interviews.

Across the entire concept inventory, “stellar” was changed to “star’s” and “temperature” was changed to “surface temperature.” Finally, all questions were reordered to better separate questions on similar concepts. Changes to individual items are provided in Table 6.

Table 6

Description of Changes to Individual Items on Concept Inventory, Version 1 to Version 2

Version 1 Item #	Changes to Item	Version 2 Item #
1	4 distracters changed to reflect students' ideas/language	1
2	Rewritten to compare Sun to other stars	17
3	Stem and distracters reworded for clarity	10
4	1 distracter changed to reflect students' ideas/language	27
5	No change	19
6	2 distracters changed to reflect students' ideas/language	13
7	1 distracter changed to reflect students' ideas/language	20
8	No change	21
9	Rewritten to compare Sun to other stars	6
10	Added explanations to 2 distracters, reflecting students' ideas/language	18

Version 1 Item #	Changes to Item	Version 2 Item #
11	Rewritten to focus on intrinsic properties rather than motion	23
12	No change	12
13	1 distracter changed to reflect students' ideas/language	28
14	1 distracter changed to reflect students' ideas/language	15
15	No change	8
16	1 distracter changed to reflect students' ideas/language	5
17	No change	9
18	2 distracters changed to reflect students' ideas/language	14
19	2 distracters changed to reflect students' ideas/language	24
20	Stem and distracters changed to reflect students' ideas/language	7
21	No change	30
22	Stem and 1 distracter changed to reflect students' ideas/language	16
23	1 distracter changed to reflect students' ideas/language	22
24	No change	26
25	No change	3
26	No change	11
27	Rewritten to compare Sun to other stars	29
28	2 distracters removed (not enough information given)	4
29	No change	25
30	No change	2

Version 2 of the concept inventory (see Appendix H) was administered as a posttest to the participating classes during the last two weeks of the Spring 2005 semester. One of the ES 101 sections was unable to be scheduled, and so was not included in the posttest administration. A total of 469 ASTRO 101 and 76 ES 101 students completed the posttest.

Version 2 was again divided into two different formats with multiple forms each. Version 2a contained all multiple-choice questions, while Version 2b contained multiple-choice plus “explain your reasoning.” The 30 content questions were again distributed over multiple forms (two for Version 2a and four for Version 2b) to reduce administration time.

Upon analysis of the Version 2 results, additional changes were made to the concept inventory, and a new version (2.5) was created. The detailed changes are presented in Table 7. Nine of the 30 questions were unchanged after the analysis, though all questions were again reordered. Distracters were changed in two questions to ensure that if nuclear fusion was an option, nuclear fission was also included as a choice. Twelve questions were changed to improve clarity or to better reflect students’ ideas and language. Finally, seven questions were removed for being too low-level or outside the scope of the topics of star properties and formation. Three new questions were created that each compared the values of a property (surface temperature, luminosity, or diameter) between the Sun, a red giant, or a white dwarf. The resulting Version 2.5 contained 26 content questions. At this time, the name “Star Properties Concept Inventory,” or SPCI, was adopted.

Table 7

Description of Changes to Individual Items on Concept Inventory, Version 2 to Version 2.5

Version 2 Item #	Changes to Item	Version 2.5 Item #
1	5 distracters changed to reflect students' ideas/language	16
2	No change	2
3	No change	6
4	Rewritten for clarity	23
5	No change	1
6	Rewritten for clarity, made "extremes" instead of "nearly"	3
7	Changed solar masses to "times the mass of the Sun"	5
8	No change	7
9	Removed – low-level knowledge question	--
10	Rewritten for clarity	8
11	Removed – not addressed explicitly enough in classes	--
12	No change	10
13	No change	11
14	1 distracter changed to pair fusion and fission	12
15	1 distracter changed to reflect students' ideas/language	14
16	Removed – low-level knowledge question	--
17	Rewritten for clarity	15
18	Rewritten for clarity	17
19	No change	18
20	Removed – stellar evolution, beyond scope of study	--
21	No change	20
22	Rewritten for clarity	21
23	Removed – planet/star comparison low priority	--
24	Rewritten for generality	4
25	Distracters shortened; 1 distracter changed to pair fusion and fission	22

Version 2	Changes to Item	Version 2.5
Item #		Item #
26	1 mass changed, 4 distracters changed accordingly	24
27	No change	25
28	Removed – low-level knowledge question	--
29	Rewritten for clarity	26
30	Removed – planet/star comparison low priority	--
	NEW question	9
	NEW question	13
	NEW question	19

In order to assess the validity of the content of the SPCI Version 2.5, a panel of experts was recruited to review the concept inventory. Reviewers were recruited through the *Astrolrner* electronic mailing list (a virtual community of astronomy educators); volunteers were asked to both answer the questions as well as provide comments about the questions. A total of 26 people returned their responses and comments. Nineteen of the reviewers have Ph.D.'s, and six have Master's degrees. Twelve of the reviewers' degrees are in astronomy or astrophysics, seven are in physics, and three are in other sciences (with four in non-science fields). Twenty-four of the reviewers teach at a 2-year or 4-year college or university, and their teaching experience ranges from 1 to 30 years. The average score on the 30 questions included in Version 2.5 was 25, or 95%. See Appendix I for all documents relating to the expert review, including the recruitment email, instructions, instrument, reviewer comments, and response letter to reviewers.

Based upon the results of the expert review, changes were made to create Version 3 of the SPCI. In addition to some wording changes on 11 questions for clarity based

upon the comments received, two questions were determined to be ambiguous and were removed. Two questions were reworded to avoid leading participants to a correct answer on other questions. Six questions were unaltered for use in Version 3. The details of these changes are presented in Table 8.

Table 8

Description of Changes to Individual Items on Concept Inventory, Version 2.5 to Version 3

Version 2.5 Item #	Change to Item	Version 3 Item #
1	Rewritten for clarity	1
2	Rewritten for clarity	2
3	Rewritten for content accuracy	3
4	Rewritten to avoid leading answers	4
5	Labels changed; Sun references removed	5
6	Rewritten to avoid leading answers	6
7	Rewritten for clarity	7
8	Rewritten for clarity	8
9	Rewritten for clarity	9
10	Labels changed	10
11	No change	11
12	Removed – repetitive	--
13	Rewritten for clarity	13
14	No change	14
15	Removed – ambiguous	--
16	Rewritten for clarity	15
17	Rewritten for clarity	16
18	No change	17
19	Rewritten for clarity	18
20	No change	19
21	No change	20
22	Rewritten for clarity	12
23	Specifics added to remove ambiguity	21
24	Labels changed; Sun references removed; Rewritten for clarity	22
25	No change	23
26	Removed – ambiguous	--

The SPCI Version 3 (Appendix J) was administered at the beginning of the Fall 2005 semester to five sections of the ASTRO 101 course, as well as three sections of ES 101. Approximately 1,100 students participated in this portion of the study. Students responded to the survey on Pearson NCS® scannable forms to facilitate rapid collection of response data (previously participants simply recorded their answers on the concept inventory itself).

The same participants completed Version 3 – again on scannable forms – as a posttest during the last two weeks of Fall 2005. As had happened in Spring 2005, one of the Fall 2005 ES 101 sections did not complete the posttest because of schedule problems. A total of 489 ASTRO 101 and 155 ES 101 students completed the posttest. Item difficulty (simply the percentage of correct responses; Allen & Yen, 1979) was calculated for both the pretest and posttest administrations; results will be discussed in chapter 4.

Student Interviews (Phase II)

One of the difficulties of writing test items is knowing whether the students are interpreting the questions the same way as they were intended and if the questions are answered the same way at different times. This is known as the internal consistency of the instrument. In order to assess the internal consistency of the questions using Version 1c of the concept inventory, interviews were conducted during the Spring 2005 semester. On the concept inventory, respondents were asked to indicate their willingness to

participate in an interview (Question 31). Volunteers from the participating ASTRO 101 courses were then selected using a stratified, random-sampling approach (Seidman, 1998). Based upon their score on the concept inventory, students were ranked as high-, middle-, or low- scoring. Between 10 and 25 students from each scoring group were randomly selected and solicited via electronic mail (see Appendix L). Two or three students from each scoring group were interviewed, for a total of 18 interviews. Students were asked to complete the same survey form as they had completed at the start of the semester, this time thinking aloud as they answered the questions. They were also asked to elaborate on their responses wherever possible. Interview responses were then compared to their pretest and any differences were discussed. Finally, interview participants were also asked to look at the equivalent multiple-choice questions (from Version 1a) and describe what they would have chosen if they had received the multiple-choice format instead. Summaries of each interview and the participants' concept inventory responses are presented in Appendix M.

Limitations of the Research Design

There are some limitations of this research design that potentially constrain the generalizability of the findings. The first is that all of the data has been collected at a single institution. While there is no reason to believe that the students at this institution are dramatically different from students nationwide in terms of their demographics,

motivation toward general education coursework, or astronomy knowledge, testing this claim was beyond the scope of this study.

In the case of the interviews in both phases of the research study, volunteers were recruited without any compensation for their time and effort. Because of this, there is a self-selection effect that may bias the data (Seidman, 1998). In the case of Phase I, interviewees were randomly selected from a pool of volunteers. In Phase II, although the recruitment of interviewees used a stratified random-selection approach in order to include a range of student performances, the approach is still limited by the students who chose to participate in the interview portion of the study.

Another limitation is in the identification of the participants' background knowledge in astronomy. Following the first set of SSR surveys, participants were asked on all subsequent SSR surveys and concept inventories whether or not they had taken an astronomy class prior to the one in which they were taking the survey (if, in fact, they were part of the ASTRO 101 group rather than ES 101). One of the difficulties with this is that the university at which this research was conducted assigns a more general designation to the course, Natural Sciences, rather than Astronomy. As a result, students who have taken a section offered by the Department of Astronomy may not identify that they have taken "an astronomy course" (rather, they think of it as having taken a Natural Sciences course). It is also possible that some participants have learned astronomy through other venues, such as a physics or earth science course with a large percentage of astronomy content.

The final limitation in the generalizability of this study is in the possible match to instructors' needs. Like concept inventories developed for other topics (e.g., Halloun & Hestenes, 1985b; Hufnagel et al., 2000; Lindell & Olsen, 2002), this concept inventory strives to use students' natural language wherever possible in order to decrease the likelihood that the questions would create dissonance between the common vocabulary recognizable to students, especially prior to instruction, and the technical language that instructors hope to teach during their course. An example of arose when discussing the luminosity of a star. This is a quantity that describes the amount of energy emitted by the star per unit time, typically measured in Watts or some comparable unit. However, this is a term that students are not likely to know prior to instruction. Furthermore, it is unlikely that students make a distinction between energy output and energy output *per unit time*, at least initially. Finding an acceptable balance between the use of students' language and vocabulary was a challenge. If instructors feel that this balance has not been achieved, they may not find the concept inventory useful for their own classes. Additionally, if their course design differs dramatically than what has been assumed in the design of the research study (e.g., they have a significant larger emphasis on the solar system or, conversely, that their course includes only stars and galaxies), instructors may determine that the alignment of content is inadequate for their use. While part of the goal of the expert review was to reduce this possibility, this is itself limited by a somewhat small sample size ($N = 26$).

This chapter has described the methods used in this investigation, including information about the questions used and how the results of early questions dictated or

informed changes made on subsequent portions of the study. Limitations of the research design have also been reported. Results presented to this point have been limited to those which directly impact the design of the investigation. The detailed results of both the SSR surveys, interviews, and the concept inventories will now be presented in chapter 4.

CHAPTER 4: RESULTS

The results of the investigation are described in this chapter. First, the results for the first for Phase I of the study, which used SSR surveys and interviews to determine the range and frequency of student ideas on the topics of interest, are discussed. Note that the results for Phase I are presented thematically rather than purely chronological, as some questions were used in multiple semesters. Next the results for Phase II of the research are presented. This will include discussion on the development and testing of the Star Properties Concept Inventory, provided in order of the version created.

Phase I: An Exploratory Study on Student Understanding

The results from Phase I of the study are divided into two main sections: the SSR surveys and student interviews. The results from the SSR surveys are presented by question type, rather than chronologically, in order to facilitate a thematic analysis.

SSR Surveys

The SSR surveys were inductively analyzed for recurring themes, as described in chapter 3. An individual response could be coded for the multiple themes, and this was often the case, especially for the lengthier responses. Themes were organized in such a way that a larger theme might have subcategories (although not all did). An example of a

category with subthemes is “burning,” identified in several different questions.

Subthemes of burning include combustion, explosion/implosion, fire/flames, and unclear (i.e., the student used the word “burning” without any further explanation). Some of the themes identified were consistent across different questions; conversely, some themes were exclusive to a particular question. Whenever themes could be used for multiple questions, care was taken to identify the responses consistently across the different questions.

To organize the following discussion, the results from Phase I of the investigation are presented by question type. The first two questions presented will be “What is a star?” and “How is the light that we see from stars created?” Other questions include “How are stars formed” and a series of questions that ask students to compare stars to other objects (i.e., other stars, planets, and shooting stars) – these last questions are combined into a section called “Questions to Compare Stars to Other Objects.”

“What is a star?”

Three different survey questions (Forms A, G2, and K2) asked students to describe their idea of a star. A total of 391 students responded to this question during two different semesters. Nearly 80% of the students’ responded that a star is made of gas or a combination of gas and dust, and 43% specifically included the phrase “ball of gas” to describe a star. The next largest category of responses was that stars are in some way burning (including all of those subthemes described above); 44% of the responses included something from this category. Twenty-nine percent of the students indicated that

some kind of energy is being released by a star – respondents might have said energy, heat, light, or a combination of these. Almost a quarter of the participants described some sort of physical characteristics about stars (e.g., their size, temperature, or color), while 16% indicated something about stars' large distances from Earth. The number and percentage of responses of these and additional selected themes are presented in Table 9.

Table 9

Themes Identified in Student Responses to “What is a star?” (N = 391), Listed by Decreasing Frequency

Theme	Responses	
	N	%
Gas/Dust	309	79.0
<i>“Ball of Gas”</i>	168	43.0
<i>Plasma</i>	5	1.3
Burning	172	44.0
Energy is Released	114	29.2
Characteristics Described	90	23.0
Distance from Earth	61	15.6
Other/Unclear, answered different question	48	12.3
Sun is a Star	42	10.7
Hot/Increasing Temperature	31	7.9
Energy Present	27	6.9
Light in Sky	26	6.6
Nuclear Reactions	21	5.4
<i>Nuclear fusion</i>	14	3.6
Gravitational Force or Pull	19	4.9
Chemical Reactions	18	4.6
Undergoes Evolution	18	4.6
Gravity as a Substance	12	3.1
Nonscience or No Response	12	3.1

Note. Because responses could be coded for more than one theme, percentages may add to more than 100%. Rows that are indented and in italics represent subthemes to the larger themes.

When analyzing the results to the different forms of the question “what is a star?”, a correct answer was determined and compared to the student responses. For this

question, the correct answer included that the star is made of gas (or gas and dust) and that the star is undergoing nuclear fusion (described by the term or through an accurate description of the process). As indicated in Table 9, only four students (2%) provided answers that stated anything about “nuclear fusion,” so it is not surprising that very few student responses (9 of the 391) were classified as Correct. The majority of responses to this question were classified as Partial. The classification of all responses (as Correct, Incorrect, Partial, True but insufficient, or Wrong) is presented in Table 10.

Table 10

Classification of Student Responses to “What is a star?” (N = 391)

Classification	Responses	
	N	%
Correct	9	2.3
Incomplete	105	26.9
Partial	235	60.1
True but insufficient	17	4.3
Wrong	25	6.4

“How is the light that we see from stars created?”

One of the key ideas in understanding “what is a star” is that its source of energy is nuclear fusion in the star’s core. In addition to being a fundamental topic of astronomy, it is also addressed in the NSES (NRC, 1996). This process creates the light that we see on Earth. Several variations of the question, “How is the light that we see from stars

created?” were asked as part of Phase I (Forms F2, G3, J3, K4, and L2; see Appendix B); a total of 1071 students responded to a version of this question. Major themes identified in the responses to these questions are presented in Table 11. Nuclear fusion, the correct response, was identified in only 7% of the responses. The burning theme described above was also identified in 32% of these responses. This is particularly problematic for this question, as astronomers often call the process of nuclear fusion “hydrogen burning” – despite the process being nothing like any kind of burning we experience on Earth, including the combustion of hydrogen.

Table 11

Themes Identified in Student Responses to “How is the light that we see from stars created?” (N = 1071), Listed by Decreasing Frequency

Theme	Responses	
	N	%
Gas/Dust	393	36.7
<i>Ball of Gas</i>	61	5.7
Burning	346	32.3
Chemical Reactions	296	27.6
Internal Energy	166	15.5
Characteristics Described	126	11.8
Nuclear Reactions	118	11.0
<i>Nuclear fusion</i>	78	7.3
Motion	109	10.2
<i>Rotation, Spin, or Angular Momentum</i>	6	0.6
Other/Unclear, answered different question	104	9.7
Properties of Light	94	8.8
Reflection, Refraction, or Absorption of Light	85	7.9
Nonscience or No Response	67	6.2
Same as Sun	32	3.0

Note. Because responses could be coded for more than one theme, percentages may add to more than 100%. Rows that are indented and in italics represent subthemes to the larger themes.

For the question about how light is created in stars, the only element needed for a correct response was nuclear fusion, either the term itself or an accurate description of the process. No incorrect processes could also be included for the response to be classified as Correct. As a result, even though more than 75 students included nuclear fusion in their response, only 33 of these could be classified as Correct because they did not also contain

any incorrect statements. The classification of all responses (as Correct, Incorrect, Partial, or Wrong) is presented in Table 12.

Table 12

Classification of Student Responses to “How is the light that we see from stars created?” (N = 1071)

Classification	Responses	
	N	%
Correct	33	3.1
Incomplete	17	1.6
Partial	469	6.4
Wrong	952	88.9

“How are stars formed?”

The previous two sections have described the results of questions defining a star and the energy production process within it, leading to another set of questions (each with slightly different wording) to ask how students believe stars are formed (Forms B, C, D2, E2, and H2; see Appendix B). A total of 904 students responded to one of these questions. As in the previous question, a large number of students (61%) indicated that stars are made of gas or gas and dust. Nearly half of the students (48%) said that the material from which a star is made is brought together through some mechanism. Rarely was this mechanism indicated; for example, about 16% of the students said that gravity caused the material to come together. Major themes identified in the responses to these questions are presented in Table 13.

Table 13

Themes Identified in Student Responses to “How is a star formed?” (N = 904), Listed by Decreasing Frequency

Theme	Responses	
	N	%
Gas/Dust	551	61.0
<i>Ball of Gas</i>	57	6.3
Material Comes Together	429	47.5
<i>Gravitational Collapse</i>	142	15.7
Burning	388	31.9
Energy Present	145	16.0
Energy is Released	130	14.4
Motion	108	11.9
<i>Rotation, Spin, or Angular Momentum</i>	49	5.4
Other Sources	99	11.0
Nonscience or No Response	93	10.3
Chemical Reactions	78	8.6
Nuclear Reactions	68	7.5
<i>Nuclear fusion</i>	47	5.2
Increasing Temperature	58	6.4
Other/Unclear, answered different question	45	5.0
Nebula	37	4.1
Gravity as a Substance	26	2.9
Big Bang	18	2.0

Note. Because responses could be coded for more than one theme, percentages may add to more than 100%. Rows that are indented and in italics represent subthemes to the larger themes.

As before, elements of a correct response were identified for this question. Four elements were needed for a complete and correct response: the star will be made of gas or gas and dust; this material is pulled together because of gravity; the temperature will increase during this process; and finally, nuclear fusion begins. These four elements constitute the *minimum* information required to be considered a satisfactory response; many instructors may want their students to understand more of this complex process. Of the 904 students who answered this question, only 3 were classified as Correct. Of these students, one indicated that he had taken an astronomy course prior to the one in which he was responding to the survey; the other two responded to an earlier survey and were not asked about prior astronomy coursework. The classification of all responses (as Correct, Incorrect, Partial, or Wrong) is presented in Table 14.

Table 14

Classification of Student Responses to “How is a star formed?” (N = 904)

Classification	Responses	
	N	%
Correct	3	0.3
Incomplete	211	23.3
Partial	406	44.9
Wrong	283	31.3

Questions to Compare Stars to Other Objects

To further investigate students' understanding of stars, participants were asked in several different questions to compare stars to other astronomical objects. Three different types of objects were used across several different forms. On Forms H3 and K3, students were asked:

Are all stars the same? Indicate 'yes' or 'no' below and answer the accompanying question. Support your answer with a sketch and labels, if possible.

Yes _____	In what way(s) are all stars the same?
No _____	In what way(s) are stars different?

A total of 381 participants responded to this question. Responses were first coded for 'yes' or 'no' responses; themes were then identified within each yes or no category. One difficulty here is that some students indicated both responses, or gave reasons in both categories. The percentage of responses stating 'yes' or 'no' is given in Table 15. Most participants (86%) indicated that stars are different from one another, although they may recognize that stars are all the same type of object. For example, one student said, "No – They have different sizes, gases, heat, age. They're like snowflakes, the same basic things but completely individual at the same time" (Form K3, #041-1029-141).

Table 15

Responses to “Are all stars the same?” (N = 381)

Category	Responses	
	N	%
‘Yes’ Only	16	4.2
‘No’ Only	386	85.6
Both ‘Yes’ and ‘No’	31	8.1
Nonscience or No Response	8	2.1

Within the reasons accompanying the ‘yes’ or ‘no’ responses, themes were identified. Approximately 10 themes emerged as reasons that stars are all the same, while nearly three times as many differences between stars were described. In responding that all stars are the same, the two most frequent responses given were that stars are made of the same materials or elements (6%) or that they all give off light (3%). All identified themes for ‘yes’ are given in Table 16.

Table 16

Themes Identified in Student Responses to “In what way(s) are all stars the same?” (N = 381), Listed by Decreasing Frequency

Theme	Responses	
	N	%
Same Composition	23	6.0
All Emit Light	13	3.4
Other Reason	11	2.9
Same Formation Process	9	2.4
All in Universe	3	0.8
Nonscience or No Response	3	0.8
Go Through Same Stages	2	0.5
All Have Gravity	2	0.5

Note. Because responses could be coded for more than one theme, percentages may add to more than 100%. Rows that are indented and in italics represent subthemes to the larger themes.

Many more differences between stars were cited than were similarities (see Table 17). The most common response is that stars may have different sizes (68%), followed by different compositions (27%). In most cases, characteristics which might differ between stars were simply listed (e.g., “size and composition” might constitute an explanation under ‘no’). As indicated earlier, some participants provided reasons for different stars being the same basic objects while also listing characteristics which might vary.

Table 17

*Themes Identified in Student Responses to “In what way(s) are stars different?”
(N = 381), Listed by Decreasing Frequency*

Theme	Responses	
	N	%
Radius or Size	257	67.5
Composition	102	26.8
Luminosity, Brightness, Amount of Light Released	95	24.9
Color	71	18.6
Other Difference	67	17.6
Age or Total Lifetime	66	17.3
Stages of Evolution	64	16.8
Distance or Location	57	15.0
Temperature	52	13.6
Shape	50	13.1
Amount of Energy, Heat Released	25	6.6
Mass	21	5.5
Density	15	3.9
Gravity or Gravitational Pull	11	2.9
Nonscience or No Response	9	2.3
Binary or Multiple Star System	7	1.8
Names	6	1.6
Formation	4	1.0

Note. Because responses could be coded for more than one theme, percentages may add to more than 100%. Rows that are indented and in italics represent subthemes to the larger themes.

Responses to this question were not classified as Correct, etc., as had been done for previous questions. Both ‘yes’ and ‘no’ could be considered correct responses to this

question, depending upon the reasons that are provided with the response. This question was used to help identify the ways in which students define and describe stars.

Form J2 asked 208 participants to compare stars to planets. Like the previous question, this asked for a ‘yes/no’ response with an explanation.

Is there a difference between a star and a planet? Indicate ‘yes’ or ‘no’ below and answer the accompanying question. Support your answer with a sketch and labels, if possible.

Yes _____	Describe what you think the differences are.
No _____	Describe why you think they are the same.

Participants overwhelmingly (89%) indicated that stars and planets are different objects (see Table 18). Like in the previous questions, the analysis of this question was based on the identification of themes within the ‘yes’ or ‘no’ responses. Themes for each category are described below. The identification of an ideal correct response, like in the previous question, was difficult. In this case, a ‘no’ response could reasonably be considered incorrect. However, not all of the ‘yes’ responses and subsequent reasons would qualify as correct. For consistency of analysis with the previous question (“Are all stars the same?”), Correct, Incorrect, Partial, or Wrong classifications were not assigned to these responses.

Table 18

Responses to “Is there a difference between a star and a planet?” (N = 208)

Category	Responses	
	N	%
‘Yes’ Only	184	88.5
‘No’ Only	13	6.3
Both ‘Yes’ and ‘No’	10	4.8
Nonscience or No Response	1	0.5

As in the previous question, themes were identified for both ‘yes’ and ‘no’ responses. The most frequent explanations given for why stars are different than planets is that they are different states of matter (typically, though not exclusively, that stars are gas and planets are solid; 31%) and that stars “burn” while planets do not (25%). The range of themes is described in Table 19.

Table 19

Themes Identified in Student Responses to “Describe what you think the differences [between stars and planets] are.” (N = 208), Listed by Decreasing Frequency

Theme	Responses	
	N	%
Different States of Matter	64	30.8
Stars “Burn”	51	24.5
Other Difference	39	18.8
Stars Emit Light	36	17.3
Planets Orbit Stars or the Sun	28	13.5
Radius or Size	27	13.0
<i>Stars are Larger</i>	14	6.7
<i>Planets are Larger</i>	13	6.3
Planets have Atmospheres	18	8.7
Planets are Habitable	17	8.2
Different Composition	14	6.7
Nonscience or No Reason	14	6.7
Stars are Hotter	11	5.3
Sun is a Star	10	4.8
Stars Undergo Fusion	9	4.3
Different Mass	6	3.0
Different Gravity or Gravitational Pull	5	2.4
Stars Farther than Planets	4	1.9
More Stars than Planets	3	1.4

Note. Because responses could be coded for more than one theme, percentages may add to more than 100%. Rows that are indented and in italics represent subthemes to the larger themes.

Fewer than 5% of the participants gave reasons for citing why planets and stars are the same kinds of objects, and most of the reasons provided were offered by single

participants (and so are lumped together in “other,” 4%). Other reasons cited by more than one participant include that planets and stars look the same in the sky (2%), both emit light (1%), and are made of the same materials (1%). Details are provided in Table 20.

Table 20

Themes Identified in Student Responses to “Describe why you think [stars and planets] are the same.” (N = 208), Listed by Decreasing Frequency

Theme	Responses	
	N	%
Other Response	9	4.4
Look Same in the Sky	4	1.9
Both Emit Light	3	1.4
Same Composition	3	1.4
Both in Solar System	2	1.0
Same Formation Process	2	1.0
Nonscience or No Response	2	1.0

Note. Because responses could be coded for more than one theme, percentages may add to more than 100%. Rows that are indented and in italics represent subthemes to the larger themes.

During the final semester (Fall 2004), Forms L3, M3, and N3 asked two different questions to again investigate students’ understanding of the nature of stars by comparing them to yet another type of object: shooting stars. On Form L3, students were asked, “Other than appearing to move quickly across the sky, how is a *shooting star* different from a *star*?” Forms M3 and N3 used a different format question that required students to

consider a hypothetical student statement about the relationship between a star and a shooting star:

Your friend tells you that a shooting star is the result of a star running out of fuel and “burning out.” Do you agree or disagree with your friend? Explain why you think the statement is correct or incorrect.

A total of 236 students responded to one of these two questions.

More than a third (36%) of the participants recognized that shooting stars are completely different objects than stars, and 29% correctly identified what a shooting star is (15% said meteor while 14% said something like “space debris”). Nearly 16% either said or agreed with the idea that a shooting star is a *dying* star, or one which has lost or used up its energy. A quarter of the respondents indicated that a shooting star is some kind of object moving or falling through Earth’s atmosphere. Additional themes are described below in Table 21.

Table 21

Themes Identified in Student Responses to “How is a shooting star different from a star?” (N = 236), Listed by Decreasing Frequency

Theme	Responses	
	N	%
Different Types of Objects	85	36.0
<i>Meteor</i>	36	15.3
<i>Space debris, rocks, etc.</i>	33	14.0
<i>Asteroid</i>	16	6.8
<i>Comet</i>	14	5.9
<i>Different but unspecified</i>	11	4.7
Other	67	26.7
SS ^a Moves or Falls Through Earth’s Atmosphere	60	25.4
SS is a “Dying Star”	37	15.7
Nonscience or No Response	23	9.7
SS Moves, Stars are Stationary	12	5.1
Energy – SS has More	10	4.2
SS Leaves a Tail or Trail Behind	8	3.4
Distance – SS is Closer	6	2.5
See a Streak of Light	5	2.1
No Nuclear Fusion in SS	3	1.3
Energy – SS has Less	2	0.8

Note. Because responses could be coded for more than one theme, percentages may add to more than 100%. Rows that are indented and in italics represent subthemes to the larger themes.

^aSS = shooting star.

Form K – Matched Data

At the start of the Spring 2004 semester, each student in one ASTRO 101 section received Form K, containing three content questions. These students also completed Form K as a posttest so that precourse and postcourse responses could be compared for

individuals. The frequencies of the identified themes and classification are included in the tables above, by question. An additional analysis performed on the Form K data was to look at how the classification of Correct, Incomplete, and so on changed for individuals over the semester. A total of 184 students completed Form K, with 62 of those completing the form as a pretest or posttest *only*.

Form K2 asked students to describe a star, and responses were classified as Correct, Incomplete, and so on as described in chapter 3. The classifications were ranked from most to least desirable in the following manner: Correct, Incomplete, Partial, True but insufficient, and Wrong. Because the classifications could be ranked, it was determined whether a student “improved” (i.e., moved from a less desirable classification to a more desirable one) or “worsened” (moved from a more desirable classification to a less desirable one). Of the 122 students who completed the survey at both administrations, 40% exhibited no change on this question over the semester. A third of the participants improved their classification, while 10% worsened. The movement between each of the classifications is shown in Table 22.

Table 22

Forms K2 and K4 Classification Change from Pretest to Posttest (N = 122)

Classification Change	K2		K4	
	N	%	N	%
Improvement				
Wrong to Partial	2	1.6	34	27.9
Wrong to Incomplete	4	3.3	5	4.1
True to Incomplete	1	0.8	0	0.0
Partial to Incomplete	24	19.7	0	0.0
Wrong to Correct	2	1.6	44	36.1
Partial to Correct	18	14.8	5	4.1
Incomplete to Correct	10	8.2	2	1.6
No Change	49	40.2	30	24.6
Worsened				
Incomplete to Partial	10	8.2	0	0.0
Partial to Wrong	2	1.6	2	1.6

Responses to Form K4, asking how light from stars is created, were also classified as Correct, Incomplete, Partial, True but insufficient, or Wrong. An analysis of movement between classifications shows that 74% of the participants improved their response on this question, while only 2% worsened. A quarter of the students exhibited no change in the classification of their response.

Because Form K3 (which asked students to describe differences or similarities between stars) was not classified as Correct, Incorrect, and so forth, no further analysis beyond the calculation of frequency of themes was performed.

Student Interviews (Phase I)

Seven interviews were conducted with volunteers from the participating ASTRO 101 courses during the Fall 2003 semester. Summaries of each interview, along with any sketches drawn by the participants, are provided in Appendix E. Overall, students' responses to interview questions were very similar to what had been observed in the SSR survey responses to that point, thus serving to validate the interpretations of the SSR survey responses. Some of the interview questions (in particular those which asked students to compare stars to planets) were adapted for use in later SSR surveys.

Summary of Phase I Results

The SSR surveys provided a large amount of data and critical insights into students' ideas about stars, their properties, and how they form. The common themes observed in these SSR survey questions were used to develop distracters to multiple choice questions for the Star Formation Concept Inventory (SFCI), Version 1, which is described in the next section.

Phase II: Development and Testing of the Concept Inventory

In Phase II of the study, the results of Phase I were used to inform the development of a concept inventory on the topics of star properties and formation. In this section, the design and testing of this concept inventory will be described by version.

Changes made between different versions were described in chapter 3. In all cases, the alpha level used to determine significance was $p < 0.01$.

Version 1 – Pretest, Spring 2005

SFCI Version 1 was administered to 796 students in ASTRO 101 courses and another 169 students in ES 101 courses. Version 1 was divided into multiple forms and different formats, in order to (a) test the internal consistency of the questions and (b) reduce the overall time required to take the survey. The breakdown of students who completed each form is given below in Table 23. Because no question was repeated within a different format, each question was answered by approximately 160 students in multiple-choice format (Versions 1a or 1b, with two and four different forms, respectively) and another 80 students in open-ended format (Version 1c, with six different forms). A percent score was calculated for the multiple-choice format surveys based only upon the number of correct answers possible (i.e., if the student had Version 1a-1, with questions 1-15, his or her score was calculated out of 15). The mean score for all participants from this pretest administration was $40.1\% \pm 18.4\%$ ($N = 481$). The mean score of ASTRO 101 students only was $39.3\% \pm 18.4\%$ ($N = 396$), while that of the ES 101 students only was $43.6\% \pm 17.9\%$ ($N = 85$). An independent-samples, two-tailed t -test showed that the difference between these scores is not significant, $t(479) = -1.974$, $p < 0.01$.

Table 23

Number of Students Completing Different Formats of SFCI Version 1 (N = 965), From Both ASTRO 101 and ES 101 Sections

Format	Form					
	1	2	3	4	5	6
1a (all multiple-choice)	78	81	--	--	--	--
1b (multiple-choice + explain)	79	81	81	81	--	--
1c (open-response)	81	82	81	81	78	81

Note. A dash (--) indicates that there was no form of that number for the given format.

An attempt was made to score the open-response questions of Version 1c by matching the students' written responses to the choices provided on the multiple-choice format of Versions 1a and 1b. In the event that a response could not be matched to one or more choice, the collection of unmatched responses was analyzed for themes in the same manner as that used for the SSR surveys in Phase I. The themes that emerged from the Version 1c responses were then compared to the distribution of responses to the choices provided on Versions 1a and 1b. If a newly-emerged theme had a higher frequency of responses than one of the choices, that distracter was changed to reflect the higher-frequency response when developing SFCI Version 2.

An example of this process is illustrated by the analysis of the following question. The multiple-choice version of Question 16 on Version 1 was:

Stars are made mostly of which element when they first form?

- a. helium
- b. hydrogen
- c. carbon
- d. oxygen
- e. silicon

The distribution of responses on Versions 1a and 1b was: (a) helium – 7%; (b) hydrogen – 60%; (c) carbon – 26%; (d) oxygen – 3%; and (e) silicon – 1%. The phrasing of the question had to be changed slightly for Version 1c, as follows:

Stars are made mostly of which elements when they first form? Why?

For the responses which could be matched to the multiple-choice options, the distribution was: (a) helium – 10%; (b) hydrogen – 32%; (c) carbon – 11%; (d) oxygen – 7%; and (e) silicon – 0%. Other responses were included by 65% of the participants (the total was greater than 100% because students could list more than one element). Included in the “others” category were the elements nitrogen, iron, boron, and mercury, plus other substances such as carbon dioxide, ammonia, water, air, dust, rocks, and minerals.

Because nitrogen was provided by about 5% of the respondents on Version 1c, it replaced option “(e) silicon” on Version 2. The new question then read:

Stars are made mostly of which types of atoms when they first form?

- a. oxygen
- b. nitrogen
- c. carbon
- d. helium
- e. hydrogen

Note that options a-e were re-ordered in this and other questions to better distribute the correct answers across the whole survey. The results from Version 1 were very informative and helped to guide the development of Version 2, in order to better reflect

students' ideas and language and therefore provide questions that better match the knowledge state of students.

Student Interviews About Version 1

During the Spring 2005, 18 interviews were conducted with participants who were selected through a random, stratified approach. Students were selected based upon a high, medium, or low score (as determined by dividing the range of scores in thirds) and distributed over the six different formats of Version 1c (each with five questions). Interview participants were asked to retake their concept inventory, this time thinking aloud as they answered the questions. They were then asked about any differences between their precourse responses and their interview responses, and to indicate which choice they would have selected on the equivalent multiple-choice format questions.

Overall, students were quite consistent with their responses between the precourse administration and the interviews. In the 40 (out of 90 total, or 45%) questions where an answer changed, it was attributed to either recently learning something about it in class or that in both instances the participant was guessing, and simply happened to guess different things. Upon questioning the change in two additional responses, participants expressed surprise at their original, pretest answer and suggested that they had simply been mistaken on the pretest. In over half of the responses (53%) there was no significant change over the period from pretest to interview. The high occurrence of participants providing the same response to the questions is indicative of the instrument's internal consistency.

When asked to indicate the multiple-choice response they would have selected, a total of 48 of the 90 questions (53%) were answered correctly over all 18 interviews. Because of the low number of possible questions (five), individual percentage scores were not calculated. The overall percentage is higher than the precourse administration mean of the multiple-choice formats, perhaps the result of conducting the interviews partway through the semester in which the participants were learning astronomy.

Version 2 – Posttest, Spring 2005

During the last two weeks of classes, Version 2 was administered as a posttest. A total of 545 students took the posttest, from six ASTRO 101 and one ES 101 sections. This was only 56% of the number of pretest participants, and can be attributed to three factors. On an individual level, many students had either dropped the course or were not in attendance on the day of the posttest. Posttest attendance rates in each section ranged from 45% to 85% of the pretest attendance. Additionally, one of the ES 101 instructors who had agreed to participate in the study was unable to schedule the posttest before the end of the semester.

In this case, only two formats were used (Version 2a, all multiple-choice, and Version 2b, multiple-choice plus explain-your-reasoning). The results of the two formats were compared to check for internal consistency of the questions. The formats were again divided into multiple forms to reduce administration time. The number of students who responded to each of the different forms is presented in Table 24.

Table 24

Number of Students Completing Different Formats of SFCI Version 2 (N = 545), From Both ASTRO 101 and ES 101 Sections

Format	Form			
	1	2	3	4
2a (all multiple-choice)	92	91	--	--
2b (multiple-choice + explain)	92	91	90	89

Note. A dash (--) indicates that there was no form of that number for the given format.

As with Version 1, percentage scores for Version 2 were calculated out of the number of questions possible (e.g., out of eight possible for Form 2b-1). The mean score for all students was $54.9\% \pm 22.6\%$ ($N = 545$). The mean score for the ASTRO 101 students was $58.5\% \pm 21.1\%$ ($N = 469$); for the ES 101 students, the mean was $32.4\% \pm 18.8\%$ ($N = 76$). A one-sample, two-tailed t-test showed that the difference between the ASTRO 101 pretest and posttest scores is statistically significant at the $p < 0.01$ level, $t(468) = 19.754$. The same type of test showed that the difference between the ES 101 pretest and posttest scores is also statistically significant at the $p < 0.01$ level, $t(75) = -5.197$. At this time it is not known why the ES 101 scores would drop over the semester, although one possible cause is that the populations were different as a result of attrition and the absence of one of the ES 101 sections in the posttest.

A one-way ANOVA showed that the ASTRO 101 mean posttest score is significantly higher than the ES 101 mean scores at an alpha level of $p < 0.01$, $F(1, 543) = 103.351$. Although the mean ASTRO 101 score would be considered a failing grade

under most grading systems, the ASTRO 101 students scored significantly higher than the ES 101 students after instruction, as expected.

During the Summer 2005, changes were made to the concept inventory based upon the results of Version 2. The details of these changes were outlined in chapter 3. A new version, Version 2.5, was created; at this time the instrument was renamed the Star Properties Concept Inventory (SPCI) to better reflect the majority of the content. Version 2.5 was then reviewed by a panel of volunteer astronomy instructors as described in chapter 3.

Based upon the results of the Expert Review, changes were made to create the SPCI Version 3. For example, several reviewers commented on the language used in questions about the luminosity of stars. Luminosity, the energy emitted by a star per unit time, is a term that most students would not be expected to know prior to instruction, and so it had not been used in Versions 1 or 2. However, the substitute language that had been used (such as brightness), although more “student-friendly,” was not accurate and could have been confusing for students after instruction. As a compromise, the phrase “energy output (luminosity)” was used in all questions dealing with this concept. Another change was that in questions that compared two stars, the generic labels such as “Star A” were changed to use letters that are not used in the spectral classification of stars so that the label could not be confused with information about the star’s spectral type.

At this point some questions were removed from the inventory. There were a series of questions that attempted to assess students’ understanding of the Sun’s properties in relationship to those of other stars. Astronomers typically consider the Sun

to be an “average star,” in that it does not fall at any extreme of possible values of its measurable properties such as temperature, luminosity, or mass. However, whether the Sun could be considered “near the high end,” “near the low end,” or “near the middle” of the range of possible values of any of these properties depends upon whether one considers the magnitude of the values (some of which are measured on logarithmic scales) or the number density of stars with that value of the property in question. To give a more concrete example: A star’s mass is typically measured in relationship to the Sun’s mass (so the Sun is defined as having “one solar mass,” typically written as $1 M_{\odot}$). Stars have been measured up to $125 M_{\odot}$; on the other end, a minimum mass of about $0.08 M_{\odot}$ is required for the core of the star to obtain the temperature and density required for nuclear fusion to begin. Thus the Sun *appears* to fall in the middle of the range of possible masses, if orders of magnitude are considered. However, when you consider the values themselves, we see that this is problematic – notice that 1 is actually much closer to 0.08 on a number line than to 125 – and a correct answer to such a question would have to be that the Sun falls at the low end of the range of possible masses. A second difficulty arises when one considers that the number of stars whose mass is about $1 M_{\odot}$ or less far outweighs the number of stars whose mass is greater than the Sun, and so if number density is taken into account, the Sun is actually *more massive* than most other stars. As questions such as these were reviewed, it became apparent that identifying a single correct answer was inappropriate, and the questions about how the Sun compares to other stars with regards to the range of properties such as luminosity and mass were removed.

With the feedback from the expert review, changes were made to Version 2.5 as described in detail in chapter 3. These changes primarily consisted of the removal of questions as described above as well as wording changes to improve the clarity of the question stem or distracters. The results of the SPCI Version 3 testing will be discussed in the next section.

Version 3 – Fall 2005

After removing questions such as those described in the previous section, Version 3 of the SPCI contained 23 content questions, plus questions on gender and prior astronomy (see Appendix J for the concept inventory). A single format was used, so that each participant had the same concept inventory with all 25 questions. Version 3 was administered as a pretest on the first day of class during the Fall 2005 semester, and as a posttest during the final two weeks of the semester. Five sections of ASTRO 101 and three of ES 101 participated in the pretest; one of the three ES 101 courses did not participate in the posttest because of scheduling problems. The total number of students who participated is presented in Table 4.

In previous semesters, for both the SSR surveys and Versions 1-2 of the concept inventory, all responses were used to calculate the statistics reported above. For the analysis of Version 3, an effort was made to remove any data which might have been incomplete or harum-scarum. For example, if a student left more than two questions unanswered, his or her data were removed (this was particularly important to avoid bias on early questions as a result of students not finishing the entire concept inventory).

Likewise, answer sheets which had obviously been carelessly completed – such as by entering “B’s” for a disproportionately large number of the 25 questions or providing answers that were not options for certain questions – were removed, as it was deemed unlikely that the student made an honest effort to answer the questions. The participant breakdown by class is described in Table 25, with both “raw” (all participants) and “reduced” groups presented (where individual student results were removed for the reasons just described). From this point forward, all results will be presented for the “reduced” groups.

Table 25

Number of Participants for SPCI Version 3, by Course Type

Administration	<i>N</i>	
	ASTRO 101	ES 101
Pretest		
Raw	690	411
Reduced	586	334
Posttest		
Raw	489	155
Reduced	417	113

The mean pretest scores for the groups were $31.2\% \pm 12.4\%$ for the ASTRO 101 students ($N = 586$) and $31.1\% \pm 12.8\%$ for the ES 101 students ($N = 334$). Using a one-way ANOVA, it was found that the difference between these scores is not statistically significant at the $p < 0.01$ level, $F(1, 918) = 0.007$. It can be inferred from these data

that, regarding the topics of star properties and formation, the pre-instructional knowledge level of the students in the control classes (ES 101) is essentially the same as that of the students in the ASTRO 101 courses.

The posttest mean for the ASTRO 101 course increased to $51.0\% \pm 17.3\%$ ($N = 417$). The frequency of responses on each question by the ASTRO 101 participants is presented in Appendix K. A one-sample, two-tailed t -test showed that the difference between the ASTRO 101 pretest and posttest scores is statistically significant at the $p < 0.01$ level, $t(416) = 23.339$. The same type of test showed that the ES 101 posttest ($29.6\% \pm 13.2\%$, $N = 112$) is not statistically significantly different than the ES 101 pretest score at $p < 0.01$, $t(111) = -1.183$. A one-way ANOVA showed that the ASTRO 101 and ES 101 posttest scores are significantly different from one another at the $p < 0.01$ level, $F(1, 527) = 147.375$. The change in scores is shown graphically in Figure 1.

Figure 1. Comparison of pretest and posttest mean scores on SPCI Version 3 for both groups. The differences between the ASTRO 101 pretest means and between the ASTRO 101 and ES 101 posttest means are significantly different at the $p < 0.01$ level.

The tests described in the previous two paragraphs include any student who took either the pretest or the posttest and met the criteria for “useable” data. However, a more robust analysis includes the analysis of matched pairs, including only those students who took both tests. There were a total of 417 participants who took both the pretest and posttest and had useable data on both. Eighty-three of these were ES 101 students, while 334 were in the ASTRO 101 course. Paired t-tests were performed to determine whether the pretest means of each group were significantly different from the respective posttest

means, at the $p < 0.01$ level as before. The ASTRO 101 pretest and posttest means for matched pairs were $30.8\% \pm 11.9\%$ and $51.5\% \pm 16.8\%$, respectively. A paired t-test showed that these scores are different at the $p < 0.01$ level, $t(333) = -21.679$. The ES 101 pretest and posttest means for matched pairs were $31.4\% \pm 13.1\%$ and $29.1\% \pm 12.6\%$, respectively. A paired t-test showed that these scores are not different at the $p < 0.01$ level, $t(82) = 1.825$.

These results successfully demonstrate the ability of the SPCI Version 3 to measure change in students' knowledge on the topic of star properties and formation over an ASTRO 101 course. Further analysis, which will be described in the next sections, includes the calculation of Cronbach's alpha, effect size, and normalized gain for the entire instrument, as well as item difficulty and discrimination for each question and the analysis of groups of questions that follow a particular theme.

Cronbach's Alpha and Effect Size

One measure of the reliability of an instrument is the coefficient α , frequently called Cronbach's α . This measures the internal-consistency reliability, or the degree to which the different items on an instrument measure the same phenomenon (Pedhazur & Schmelkin, 1991). Using the ASTRO 101 posttest participants ($N = 417$), a value of 0.735 was calculated for Cronbach's alpha for the 23 items. This can be interpreted to mean that 73.5% of the variance of the total scores is a reliable variance (as opposed to random).

The t-tests described in the previous section showed that the difference between pretest and posttest means for the ASTRO 101 course is statistically significant. A way of measuring the magnitude of this difference is to calculate the effect size, which describes the difference in units of standard deviation. There are several different methods of calculating effect size; for this study Cohen's d was calculated (Thalheimer & Cook, 2002). The formula for this calculation is

$$d = \frac{\bar{X}_t - \bar{X}_c}{\sqrt{\frac{(N_t - 1)s_t^2 + (N_c - 1)s_c^2}{N_t + N_c}}},$$

where the subscript t refers to the treatment (in this case the posttest) and c refers to the comparison group (here the pretest). Cohen suggested that values above 0.20 are small, above 0.50 are medium, and above 0.80 are large effects (as cited in Thalheimer & Cook). The calculated Cohen's d for this study was 1.35, what Thalheimer and Cook consider a "very large effect."

Item Difficulty and Item Discrimination

The item difficulty of a question, p , is defined simply as the proportion of students who got the answer correct; thus items with lower difficulty values are "harder" questions than those with higher difficulty values (Allen & Yen, 1979). Item difficulty could also be thought of as the inverse of "item easiness." The difficulty of each item (Questions 1-23) was calculated for both pretest and posttest and is presented in Table 26. This table also presents the item discrimination (described below) and the percentage of responses for the correct answer and the most common distracter, all from the posttest.

Table 26

Item Analysis of Questions on SPCI Version 3, ASTRO 101 Students Only (N = 417)

Item	p^a		r_{ix}	Answer (%)	
	Pretest ^b	Posttest	Posttest	Posttest Correct Response	Posttest Most Common Distracter
1 – Stellar composition	0.420	0.736	0.397	E (73.6)	D (9.8)
2 – Cause of temperature increase during formation	0.176	0.161	0.288	D (16.1)	A (58.8)
3 – Sun's surface temperature	0.176	0.204	0.178	B (20.4)	C (53.0)
4 – Location of energy production	0.635	0.801	0.392	C (80.1)	D (7.7)
5 – Relationship between mass and fusion rate	0.128	0.319	0.353	A (31.9)	B (41.7)
6 – Dominant force during formation	0.410	0.585	0.399	B (58.5)	E (28.1)
7 – Relationship between temperature and color	0.352	0.746	0.395	C (74.6)	B (17.7)
8 – Balance between gravitational pull and pressure	0.369	0.365	0.324	E (36.5)	D (26.4)
9 – Comparing surface temperature of Sun/RG/WD ^c	0.379	0.475	0.263	B (47.5)	A (23.7)
10 – Relationship between mass and lifetime	0.237	0.614	0.440	B (61.4)	A (18.7)
11 – Definition of a protostar	0.321	0.633	0.446	A (63.3)	B (25.2)

Item	p^a		r_{iX}	Answer (%)	
	Pretest ^b	Posttest	Posttest	Posttest Correct Response	Posttest Most Common Distracter
12 – Sun’s energy production process	0.164	0.388	0.551	B (38.8)	A (20.6)
13 – Comparing mass of Sun/RG/WD	0.256	0.168	0.110	D (16.8)	A (66.9)
14 – Stars begin as gas/dust	0.814	0.918	0.340	E (91.8)	B (2.6)
15 – Definition of a star	0.230	0.499	0.536	D (49.9)	C (28.1)
16 – Temperature’s effect on apparent brightness	0.517	0.691	0.280	B (69.1)	C (11.5)
17 – Relationship between mass and lifetime	0.316	0.743	0.500	B (74.3)	A (13.7)
18 – Comparing luminosity of Sun/RG/WD	0.125	0.319	0.362	A (31.9)	B (35.3)
19 – Creation of light in stars	0.208	0.441	0.411	C (44.1)	D (21.6)
20 – Rank of colors by temperature	0.218	0.492	0.395	D (49.2)	A (24.0)
21 – Comparing luminosities of stars	0.369	0.662	0.482	D (66.2)	C (15.3)
22 – Relationship between mass and lifetime	0.067	0.194	0.486	E (19.4)	D (35.0)
23 – Mass determines evolutionary fate	0.292	0.573	0.407	E (57.3)	B (16.8)

Note. ^a p is item difficulty. ^b $N = 586$ for pretest. ^c In the description of items 9, 13, and 18, RG = red giant and WD = white dwarf.

Item discrimination indicates “the degree to which responses to one item are related to responses to the other items on the test” (Allen & Yen, 1979, p. 120). The

measure of item discrimination used in this analysis is the item/total-test-score point biserial correlation, r_{iX} , defined as

$$r_{iX} = \frac{\bar{X}_i - \bar{X}}{s_X} \sqrt{\frac{p_i}{1 - p_i}},$$

where i refers to the item number; $\bar{X}_i$ to the mean score of students who got item i correct; $\bar{X}$ and s_X to the mean and standard deviation, respectively, of the scores among all students; and p_i to the item difficulty. Item discrimination values are reported in Table 26. As with item difficulty, a wide range of point biserial values is desirable to ensure that performance on the test is indicative of the varying knowledge levels of all students.

Ideally the item difficulty should be higher (i.e., the questions are answered correctly by more students) on the posttest administration than the pretest. For the ASTRO 101 students who completed the SPCI Version 3, this is true for all but three of the questions, Questions 2, 8, and 13. Looking only at the item difficulty, however, is insufficient to determine if the question should be removed from the test; item discrimination and the most common distracter should also be reviewed. At this time, each of the three questions with a decreased item difficulty will be examined.

Question 2 asks about the cause of the temperature increase that occurs in stars during formation; its item difficulty decreased from 0.176 to 0.161. The question reads:

2. Which of the following causes a star's interior temperature to increase during its formation?
 - a. Nuclear fusion causes gravitational collapse, which generates heat.
 - b. Heat is generated when the star's gravity contracts.
 - c. Gravitational collapse involves the generation of heat from chemical reactions.
 - d. During collapse, gravitational potential energy decreases while its temperature increases.

The correct answer for this question is (d). On the pretest, the distribution of responses across the four choices was fairly even: (a) 37.0%; (b) 23.4%; (c) 22.0%; and (d) 17.6%.

On the posttest, there is a definite shift toward response (a), with 58.8% of the selections (other responses: (b) 10.3%; (c) 14.9%; and (d) 16.1%). If students have learned that nuclear fusion could be considered the “end” of the formation process, as it constitutes the defining characteristic of a star, then it is easy to see how response (a) would be an attractive distracter. Furthermore, if the presentation of details during classroom instruction on the formation process is limited in the ASTRO 101 course, the relationship between gravitational potential energy and temperature increases are likely to remain unclear. The item discrimination for this question was 0.288, an acceptable value for test design.

The item difficulty of Question 8 dropped slightly from 0.369 to 0.365 from pretest to posttest. This question asks:

8. Why don't most stars collapse in on themselves under gravity's influence?
 - a. Material churning in and out of the center of the star balances gravity.
 - b. The internal structure of the star holds the surface out and keeps it from collapsing.
 - c. Gravity from planets orbiting the star pulls outward on the star's material.
 - d. The force from particles ejected outward from the center of the star balances gravity.
 - e. Gas pressure caused by energy created in the star pushes outward to balance gravity.

The best answer for this question is (e). It is interesting to note that the response which had the largest gain in response was (d). There are some particles, as well as photons, emitted during nuclear fusion; the knowledge of this may be part of the source of confusion. Again, this is a question which may remain particularly difficult if the details of hydrostatic equilibrium (the balance between gravitational collapse and gas pressure) are not discussed in an ASTRO 101 course. As with Question 2, the item discrimination for Question 8 (0.324) was acceptable.

Finally, Question 13 had a decrease in item difficulty from pretest (0.256) to posttest (0.168). It asks,

13. Which of the following objects is most massive: a red giant, a white dwarf, or the Sun?
- a. A red giant is always the most massive.
 - b. A white dwarf is always the most massive.
 - c. The Sun is the most massive.
 - d. These objects could have the same mass.

Although the names would imply that a red giant is the most massive, the terms “giant” and “dwarf” actually refer to radius rather than mass. A star like the Sun will, at the end of its main sequence lifetime, become a red giant, and will eventually evolve into a white dwarf. This implies, then, the correct answer: (d) these objects could have the same mass. In the participants’ responses, however, there is a dramatic increase in the number of respondents who chose (a), with a reduction in response for (c) and (d). Like may be the case for Question 2, a lack of focused instruction may contribute to student difficulties on Question 13. This item’s discrimination is low (0.110) because of the low percentage of students who chose the correct response (only 16.8%).

The item difficulty provides a way of determining whether any individual item is “too easy or too hard,” with respect to how many students correctly answered that question. Although some of the items from SPCI Version 3 have low item difficulty, the overall average (0.51) implies that the distribution of item difficulty is reasonable. No items have been marked for removal as a result of too-low or too-high item difficulty. This decision is supported by also evaluating the item discrimination and the nature of the highest-selected distracter. The next section will look at groupings of questions that are each related to a particular concept or theme.

Normalized Gain

Another analysis of the SPCI Version 3 data was performed. Widely used in physics education research is the *normalized gain*,

$$\langle g \rangle = \frac{\% \langle post \rangle - \% \langle pre \rangle}{100\% - \% \langle pre \rangle},$$

where angled brackets indicate class averages (Hake, 1998). Using this measure, we find that the normalized gain for the ASTRO 101 course is $\langle g \rangle = 0.29$. Using Hake’s criteria, this is considered a low gain (p. 65). The intent of Hake’s study was to compare classes which used interactive engagement (IE) methods with classes using more traditional, primarily lecture-based (T) methods. In a review of previously released research, he found that IE courses had significantly higher normalized gains than T courses. Although a normalized gain was calculated for the ASTRO 101 course for SPCI Version 3, no

attempt has been made to define IE versus T classes and to determine whether or not the normalized gain is different between them.

Clusters of Questions that Address Particular Themes

One of the important design considerations for the SPCI was the need for multiple questions on any given topic (Nunnally, 1978). The questions on the SPCI fall into one of three major themes: nuclear fusion as the defining characteristic of stars, with 5 questions; the process of star formation, with 5 questions; and star properties, with 13 questions. The star properties could be further subdivided into four categories: temperature and color (4); mass (2); luminosity (3); and the mass-main sequence lifetime relationship (4).

The result for the themes is generally the same as the overall scores; i.e., the ES 101 courses show no gains over the course, while the ASTRO 101 course scores improve. Results of the three themes are presented in Figure 2. Figure 3 shows the scores of ASTRO 101 students on the different subthemes of the 13 star properties questions.

Figure 2. Comparison of mean pretest and posttest scores on three themes, by course type. Differences between the ASTRO 101 pretest and posttest means are significant at the $p < 0.01$ level for all three themes.

Figure 3. Comparison of mean pretest and posttest scores of ASTRO 101 participants on four subthemes in the 13 “star properties” questions. Differences between each pretest and posttest means are significant at the $p < 0.01$ level for all four subthemes.

This pattern of results – that the ASTRO 101 scores increase significantly over the instruction while the ES 101 scores do not – demonstrates that the items are working together as a single instrument in the way that was intended. If one of the themes had, for example, demonstrated a decrease in scores, those questions would have been reevaluated on an individual basis to determine whether they needed to be rewritten (because they are

too difficult or misleading) or removed (because they are beyond the scope of typical ASTRO 101 instruction).

Prior Astronomy and Gender

In addition to the 23 content questions on the SPCI Version 3, 2 “demographic” questions were asked of the participants; the analysis of the concept inventory with respect to these items will be discussed in this section. One of the non-content questions asked of participants is whether or not they had taken an astronomy class. Approximately 10% of the ASTRO 101 participants indicated that they had taken an astronomy course prior to the one in which they were taking the survey. When the ASTRO 101 scores were analyzed while taking this variable into account, it is shown that the pretest scores are significantly different across groups, $F(1, 584) = 37.023, p < 0.01$, while the posttest scores are not significantly different across groups, $F(1, 415) = 3.446, p < 0.01$. Scores are shown graphically in Figure 4. These results demonstrate that although those students who had taken an astronomy course prior to this ASTRO 101 class in which they took the SPCI scored higher on the pretest than their no-prior-course counterparts, the resulting posttest score was the same for both groups. It is possible that the content of the current ASTRO 101 course and the prior astronomy course overlapped, so it is not surprising that the posttest scores were not higher.

Figure 4. Comparison of mean pretest and posttest scores of ASTRO 101 participants, by participants' indication of having taken a prior astronomy course. Difference between the Prior and No Prior pretest means is significant at the $p < 0.01$ level; difference in the posttest means is not significant.

As well as looking at the effect of a prior astronomy course, ASTRO 101 scores were also analyzed for gender differences. Approximately 48% of the ASTRO 101 participants were female, while 52% were male. Mean scores for the male participants pretest and posttest were $33.6\% \pm 13.1\%$ and $54.2\% \pm 17.7\%$, respectively; mean scores for female participants pretest and posttest were $28.7\% \pm 11.1\%$ and $47.7\% \pm 16.1\%$, respectively. Analysis of variance of the pretest and posttest scores between gender groups determined that the scores were significantly different from one another at the $p <$

0.01 level, $F(1, 584) = 23.793$ and $F(1, 415) = 15.081$, respectively. Scores of the two groups (male and female) for the ASTRO 101 students are displayed graphically in Figure 5.

Figure 5. Comparison of mean pretest and posttest scores of ASTRO 101 participants, by gender. At the $p < 0.01$ level, differences between Male and Female means are significant at both the pretest and posttest administrations; pretest to posttest mean score increases are also significant for both Male and Female groups.

Summary

The range and frequency of student ideas about star properties and formation were determined in Phase I of this study. As has been shown in this chapter, through the results of multiple questions, many students associate stars with burning. Because students probably perceive both stars and burning within essentially the same magnitude of temperature, it is not surprising that students associate the two together. Instructors also often use some form of the word burning to describe nuclear fusion in the star's core. Results such as these have been used to design distracters to multiple-choice questions for the concept inventory. Testing has shown that although many of the distracters were attractive for students prior to instruction, these distracters may not be as attractive after instruction – or to put it another way, that the students were able to learn the correct scientific response for many of the questions as a result of their one-semester ASTRO 101 course.

CHAPTER 5: DISCUSSION

The purpose of this investigation was to determine what students understand about star properties and formation through a mixed-method research design. In this chapter, interpretations of the results will be discussed in terms of the three original research questions. Next, the implications for astronomy instruction will be described, followed by implications for astronomy education research. Finally, future research avenues will be described.

Discussion of Results in Relation to the Research Questions

As a result of the researcher's interests, the relevant background literature review, and insufficient scholarly literature about college nonscience majors conceptions about star properties and formation to guide and inform constructivist instructional strategies, three research questions were designed to guide this project. These will each be discussed in this section, followed by a summary of the findings.

Research Question 1: Prior to instruction, what do undergraduate nonscience majors who are enrolled in an ASTRO 101 course understand about stars and star formation?

Students' pre-instructional beliefs about star properties and formation were investigated primarily through the first phase of this project. In Phase I, SSR surveys and

interviews were used to determine the range and frequency of students' ideas about the questions listed in Appendix B. Through an inductive, iterative analysis of the responses, themes were identified for each of the SSR survey questions posed; these same themes were also identified in the interviews.

Overall, results showed that students' have a foundation of basic knowledge but are lacking or incorrect in some of the details. For example, in responding to the "what is a star" question, more than 80% correctly identified that a star is made of gas and 43% specifically used the phrase "ball of gas." However, few students provided any description beyond this basic idea of composition.

The primary defining characteristic of a star – that it undergoes nuclear fusion in its core – was stated by fewer than 4% of the participants prior to instruction. Instead, students who made any attempt to describe the energy production process used "burning" as the explanation. This was stated by nearly half (44%) of the participants. Through explanations in interviews, it was clear that students do not always think of "burning" as a standard combustion reaction such as that in the fire with which we are familiar. Some students recognize that the combustion processes we are most familiar with typically involve oxygen; the lack of oxygen in space, then, would prevent stars from creating light through this process. However, it was rare that students could further clarify their ideas. It is also possible that the idea that gases are often flammable (as reported in Driver, Squires, Rushworth, & Wood-Robinson, 1994) might support the idea of a star as a "burning ball of gas." On the SSR surveys, where space and time were significantly more

limited than in interviews, this kind of distinction between combustion and some other, typically unknown process was rarely explained.

The “burning” misconception was dominant in both the “what is a star” and “how is the light we see from stars created” questions. The second most common idea for this second question was that chemical reactions were the source of energy production in stars (28%). Although it is not known what percentage of these participants took a high school chemistry class, it is reasonable to conclude that this idea may have come from such prior instruction. One of the basic characteristics used to identify whether or not a chemical reaction has taken place is that it can emit heat or light (Wilbraham, Staley, & Matta, 1997); it is not surprising, then, that students might take this piece of information and misapply it to stars. Also, as has been previously stated, astronomy instructors often use the word burning in a casual manner to describe the nuclear fusion that occurs within a star’s core.

In describing how a star forms, nearly half of the more than 900 respondents indicated that material is brought together in some fashion. Again, the details are lacking, with only 16% identifying gravitational force as the cause of this process. This is not surprising when we consider that gravity is not typically discussed as a central force until high school physics at the earliest and, further, that fewer than a third of all students in public high schools take physics (American Institute of Physics Statistical Research Center, n.d.) Many of the students provided little in the way of a description of a process of formation, but rather simply provided information about specific characteristics that the process might have (e.g., composed of gas and dust, energy is released, etc.)

Many students were able to identify characteristics which might differ from one star to another or between stars and planets, such as radius, composition, distance, energy emission, and so forth. Students had more difficulty, however, distinguishing a star from a shooting star (in reality, a meteor – a piece of rock, dust, or ice, which burns as it travels through Earth’s atmosphere). A shooting star was sometimes mistaken for a dying star (16%).

The SSR surveys provided a rich amount of data on students’ pre-instructional ideas about stars. Although the level of detail varied amongst responses, students seemed willing to make a reasonable attempt at an answer (as indicated by the fact that fewer than 10% of the participants on any given question provided a nonscience or no response). Using the data from the SSR surveys, and the interviews used to ground-truth the interpretations of the SSR survey responses, a concept inventory was developed – thus addressing the second research question of the study.

Research Question 2: How can we use this knowledge to inform the development of a concept inventory to measure student understanding on the topics of stars and star formation, both before and after instruction?

In Phase II of this project, the knowledge of student beliefs about stars properties and formation gained through the SSR surveys of Phase I was used to inform the development of the Star Properties Concept Inventory (SPCI). The SPCI is a 23 multiple-choice question instrument intended to measure student learning gains over instruction, thereby providing a measure of instructional effectiveness. The SPCI uses students’

natural language, avoiding astronomical jargon wherever possible, and have distracters that are matched to known difficulties identified in Phase I. Version 3 of this instrument (Appendix J), administered to both ASTRO 101 and control ES 101 students in Fall 2005, has been shown to be able to identify student learning gains over the semester period in which the ASTRO 101 students had instruction on these topics. Validity of the instrument is further evidenced by concurrent tests of the ES 101 courses that showed no such gains, as shown in detail where no pretest to posttest changes in score exist.

While this research confirmed that the instrument could measure change in student understanding over time, it also provided the ability to identify those cases where instruction appears to have little effect on student understanding. This will be examined further in the following discussion of the third and final research question.

Research Question 3: Finally, what conceptual difficulties about stars and star formation remain after instruction on these topics, as indicated by comparing students' pre- and post-instructional scores on the concept inventory?

Although statistically significant learning gains were observed over the semester of instruction, the mean posttest score (51%) for the ASTRO 101 course might be considered an unsatisfying result for instructors. Three of the 23 items (Questions 2, 13, and 22) have a posttest item difficulty of 0.20 or less. Two of these, Questions 2 and 13, were discussed in chapter 4, as the item difficulty actually decreased over the semester. Question 2, on the cause of temperature increase during star formation, may simply prove to be a detail about which instructors do not provide enough information. This result may

also highlight a learning difficulty, which might be overcome by purposeful intellectual engagement in a learner-centered environment.

Question 13 involves comparing the characteristics of the Sun to those of other stars, and as such would at first seem to be adequately addressed in an ASTRO 101 course. Question 13 focuses on comparing the mass of the Sun to that of a red giant and white dwarf. It is probable that these comparisons are not directly taught, but rather assumed that students will understand through their understanding of the Hertzsprung-Russell (H-R) diagram. The results of this study show that this assumption may in fact be false and that such topics need to be explicitly addressed in order to facilitate deep conceptual understanding.

Finally, Question 22 also has a low item difficulty level (0.19 for ASTRO 101) post-instruction. This question asks students to infer something about lifetime based upon mass, while Question 10 is almost the opposite. Astronomers have determined that the main sequence lifetime of a star is inversely proportional to the mass raised to the ~ 2.5 power (or, $t \propto 1/M^{2.5}$; Kaufmann & Freedman, 1999). Even if learning the mathematical relationship is not expected of our ASTRO 101 students, often the general relationship (“more massive stars have significantly shorter ‘lifetimes’ than less massive stars”) is presented as part of traditional instruction. Furthermore, the high item discrimination (0.486) for this question indicates that students who have high total scores on the instrument do well on this question. The results of this study demonstrate that this is clearly still a difficult concept in which a simple verbal explanation is not sufficient, and a learner-centered intervention may be required.

The low item difficulty for the ASTRO 101 posttest scores indicates that these four questions address topics that areas are particularly difficult for students to develop deep understanding, even after instruction. This has significant implications for the teaching of astronomy if instructors have as a goal *understanding of* rather than *exposure to* astronomy topics such as stars.

The learning gains observed in this study might seem low. However, such gains are concurrent with other studies that show students only score about 50-60% correct after lecture (e.g., Bardar, 2006; Prather et al., 2004). These results have serious implications for astronomy teaching, especially when a constructivist framework is adopted. Such implications will be discussed in the next section.

Implications for Astronomy Teaching

Astronomical Jargon

Like is common in physics, some of the terms used in astronomy have very specific meanings that might conflict with our everyday use of the words (Prather, 2000; Prather & Harrington, 2001; Williams, 1999); the misconception about burning is particularly problematic in astronomy because of the language used by the community. Consider the following description of energy production in stars, taken from a popular ASTRO 101 textbook:

This process of **nuclear fusion**, by which hydrogen is converted into helium at the Sun's center, is called **hydrogen burning**, even though nothing is actually burned in the conventional sense. (The chemical reactions involved in ordinary burning act to rearrange the outer electrons

of atoms but have no effect on their nuclei.) Because it can occur only at high temperatures, hydrogen burning is called a **thermonuclear reaction**, or **thermonuclear fusion**. (Kaufmann & Freedman, 1999, p. 438)

The process of nuclear fusion, the key method of energy production in stars, is described here using four different bold-faced vocabulary words, leading to potential confusion for students who are unable to understand that the terms are intended to mean basically the same thing but physically do not. Furthermore, astronomers' use of the phrase "hydrogen burning" (and similar phrases for other nuclear fusion processes in later evolutionary stages) can lead to additional confusion.

Given this use of phrases like "hydrogen burning" in the astronomical community, one might wonder whether a response with "burning" should be allowed as a correct response to questions such as those created for the SPCI? After careful consideration it was deemed that a student who truly understands the process of nuclear fusion, she or he should be able to identify that process in name or description and distinguish it from burning.

Another important term that students have difficulty with is *energy*; this is true for physics (Williams, 1999) as well as astronomy. In this study, it was observed that students could use the terms *energy*, *light*, and *heat* interchangeably; in other instances, they were clearly considered separate ideas as one could create another (e.g., "light is created from the energy...", Form K4, #041-1029-029). It is uncertain whether many ASTRO 101 instructors take the time to carefully define what is meant by energy and heat. In contrast, because light is the only form of information we have ever received from objects outside of our solar system, the topics of light and its analysis through

spectroscopy are the most important in astronomy instruction (Bardar, Prather, Brecher, & Slater, 2005).

These examples demonstrate that there exists a potential gap between the understanding that students' have after instruction and the colloquial science language instructors (and textbooks) use to teach about these topics. This problem can only be reduced through a large-scale, systematic effort to improve the way we use astronomical jargon. Williams' (1999) suggestion, for example, to "agree among disciplines on the meanings of shared words" could be of use when talking about energy in particular (p. 676). The use of concept inventories such as the SPCI (and others in existence or development) can help to identify post-instructional problem areas and allow instructors to assess their own language and presentation of ideas to determine if changes need to be made to better facilitate student learning.

Use of Concept Inventories to Analyze Instructional Effectiveness

The SPCI is designed to be used pre- and post-instruction to measure learning gains over an instructional intervention – for example, a unit on stars or an entire astronomy course. If an instructor finds that his students, after instruction, are scoring low on the nuclear fusion-related questions, changes can be made in the teaching methods and/or materials to improve learning on the topic.

The FCI has been adopted for such use in college-level physics courses across the country. In a meta-analysis of the use of the FCI and the Mechanics Baseline (MB) tests as indicators of instructional effectiveness, Hake (1998) calculated the normalized gain

for pre/posttests of 62 introductory physics classes. He found that while the 48 interactive engagement courses achieved a gain of $\langle g \rangle_{\text{IE-ave}} = 0.48 \pm 0.14$ ($N = 4458$), the gain of the traditional courses only achieved a gain of $\langle g \rangle_{\text{T-ave}} = 0.23 \pm 0.04$ ($N = 2084$). Based upon results such as these, Hake (2005) calls for all disciplines in higher education to consider the development and use of multiple-choice instruments, in the vein of the FCI, to measure instructional effectiveness and to develop interactive engagement methods suitable for the discipline.

Call for Interactive Engagement Methods for Use in Astronomy

If physics education research has been able to show that interactive engagement methods are more effective at fostering deep conceptual understanding of physics, why should we expect astronomy to be any different? Although some interactive engagement methods have been developed, they are not yet in widespread use. *Lecture-Tutorials for Introductory Astronomy* (Adams, Prather, & Slater, 2002, 2005) have been shown to increase learning gains significantly beyond that of lecture alone (Prather et al., 2004). Similarly, Hudgins (2005) showed that regular use of *Ranking Tasks* in an ASTRO 101 course helped students to make significant learning gains beyond what was reached after lecture. Both studies illustrate that the development of research-based materials, implemented in a learner-centered classroom, can have a positive effect on student understanding of astronomy topics. The *Ranking Tasks* study, in particular, showed that these materials can be made such that initially low-achieving students can in the end score as high as initially high-achieving students post-instruction, and that these materials

and assessments do not necessarily show the gender bias that has been observed in so many other materials (Hudgins, 2005).

Implications for Astronomy Education Research

Further Research on Student Understanding in Astronomy, Including “Modern Topics” of Interest to Instructors

As the astronomy education community has grown, there has been some disagreement about the topics that should be included in an ASTRO 101 course and how astronomy education research can be used to inform decisions about that scope and design (see, e.g., Pasachoff, 2001, 2002a, 2002b; Sadler, 2001, 2002). Whether one considers the “modern topics” of astronomy to be inspirational and exciting (and therefore, a good motivator for nonscience majors) or far-removed from students’ lives (thus potentially irrelevant), a constructivist approach dictates that knowing what students’ bring with them to the class is crucial to fostering effective learning. This means that astronomy education research should support investigations into students’ understanding about modern topics. Up to this point, very little has been done on such topics (Bailey & Slater, 2003, 2005), although preliminary studies in the topics of astrobiology and cosmology have been reported (respectively, Offerdahl, Prather, & Slater, 2002; Prather, Slater, & Offerdahl, 2002). This study on stars contributes to the research base on a modern topic that is one of the most common in ASTRO 101 courses nationwide (Slater, Adams, Brissenden, & Duncan, 2001). When as many as 40% of

students in general education courses like ASTRO 101 indicate that they intend to become teachers (e.g., Lawrenz, Huffman, & Appeldoorn, 2005), it is especially important that a constructivist instructor be well-informed by research about students' preinstructional beliefs in order to create effective learning environment. By fully understanding stars, these future teachers can later use such knowledge to effectively facilitate student learning on a number of different standards.

Development of Concept Inventories to Analyze Instructional Effectiveness

As described above, Hake (2005) has suggested that the design and widespread use of multiple-choice instruments is needed to investigate instructional effectiveness in any discipline. In astronomy to this point, the predominant instrument that has been used is the Astronomy Diagnostic Test (Deming, 2002; Hufnagel, 2002; Hufnagel et al., 2000; Zeilik, 2003). However, this instrument was designed with a different purpose and covers a wide range of topics. The use of it to look at specific topics is therefore limited. Likewise, perhaps in part because of the limited time spent on the topic of lunar phases in a college-level course, the Lunar Phases Concept Inventory (LPCI; Lindell, 2001; Lindell & Olsen, 2002) has not been widely adopted.

What is needed for astronomy, then, is a suite of concept inventories that more closely align with the topic that are typically included in the ASTRO 101 course. In addition to the LPCI (Lindell, 2001; Lindell & Olsen, 2002) and the SPCI described in this study, the Light and Spectroscopy Concept Inventory (Bardar, 2006; Bardar, Prather, Brecher, & Slater, 2005) is currently in development and testing at another institution.

The Greenhouse Effect Concept Inventory (Keller, 2006; Keller, Prather, & Slater, 2006), also in development, may be of interest to some astronomy instructors or to instructors of other introductory science courses for nonscience majors, such as the ES 101 courses used in this study as a control group. The use of concept inventories to determine the effectiveness of teaching on a focused topic can be interpreted as an indication of teaching effectiveness as a whole, and this effectiveness has repeatedly been shown to be lacking (e.g., Hake, 1998; Prather, et al., 2004). Widespread use of – and research using – these concept inventories in ASTRO 101 and similar classes is needed in order to better inform the development of interactive engagement methods for these courses for nonscience majors. Concept inventories for additional topics can also be developed in conjunction with research on student understanding, so that the instruments accurately represent the range of student ideas about the topics both before and after instruction.

Future Research and Conclusions

Through the two phases of this research project, the range and frequency of pre-instructional beliefs about star properties and formation held by students in an introductory college astronomy course for nonscience majors has been determined through the use of SSR surveys, and this information has been used to inform the development of a concept inventory that can be used to measure instructional effectiveness on these topics. However, there are several avenues of further research that can be followed to build upon these results.

One possibility is the expansion of this study to related topics. This research study was deliberately focused on only a few basic properties of stars and the process of star formation. The breadth of student ideas about stellar evolution was not addressed. Data from the SSR surveys and interviews indicate that students have heard of other stages of stellar evolution – most commonly black hole, red giant, and white dwarf – and it was clear that these terms were not always used in a way that would be considered scientifically accurate. The investigation of these ideas could lead to the creation of an additional concept inventory on stellar evolution.

In this study, it was observed that male students scored significantly higher on the SPCI than female students, at both the pretest and posttest administrations. This result is consonant with other studies involving multiple choice tests, especially those in physical and earth/space sciences (see, e.g., Hamilton & Snow, 1998, and references therein). At this point it is not clear what factors produce this bias in this instrument, but further research could be conducted to investigate the result.

Another important research project that should be conducted before the SPCI becomes widely adopted is the investigation of its generalizability across institutions. After having multiple instructors at a variety of different institutions administer the SPCI both pre- and post-instruction, an analysis of the data could help determine whether the students at the researcher's home institution were, in fact, reasonably representative of other ASTRO 101 students both before and after instruction.

Once this level of generalizability is determined through an investigation such as the one described above, data can be analyzed in a manner similar to that of Hake (1998)

in investigating normalized gains of Interactive Engagement versus Traditional Lecture-based Instruction. Given the prominence of stars in most ASTRO 101 courses (Slater, Adams, Brissenden, & Duncan, 2001), the use of the SPCI to investigate instructional effectiveness could become widespread across the astronomy community. If it is determined that, like the traditional physics courses reported in Hake (1998), traditional astronomy courses are ineffective at promoting deep conceptual understanding about stars, then the development of additional interactive engagement methods or focused curricular materials designed to intellectually engage students could follow.

Overall, this research study has provided much-needed information about what ASTRO 101 students' understand about stars and star formation. The Star Properties Concept Inventory, a 23-item multiple-choice test, has been created and evaluated, and provides a valid and reliable instrument that can measure conceptual change on the topics of star properties and formation over an instructional period. The astronomical community is poised to use inventories such as these to examine instructional effectiveness as it moves toward learner-centered instruction. With further research conducted using this instrument, instructors may develop instructional methods and strategies that will lead to a deeper and more profound understanding of the properties and formation of stars.

APPENDIX A

RECRUITMENT LETTERS TO GENERAL EDUCATION PROFESSORS (PHASE I)

Summer 2003

Dear [Professor],

My name is Janelle Bailey and I am a graduate student working with Dr. Tim Slater and Dr. Ed Prather at Steward Observatory. My dissertation work is in student understanding of star formation. I am beginning to collect data for this study via student-supplied response surveys in the NATS 102 courses.

I am writing to ask your permission to administer this survey to your students on the first day of class (Monday, June 9). I am requesting this date because it is imperative that the data be collected *before* any instruction takes place. There are three different surveys that would be randomly distributed to your class, each with only a single question. The process would take less than 15 minutes. Because of a scheduling conflict, the survey would actually be administered and collected by Dr. Ed Prather.

I very much appreciate your consideration in this matter. Please let me know your decision as soon as possible.

Thank you!

Janelle Bailey

Fall 2003

Dear Professor,

I would like to ask a few moments of your time. I am starting my dissertation work on students' pre-instructional understanding of star formation and would like to survey your general education courses (NATS 102) on the first day of class. The survey would have one or two questions (if two, one on prior astronomy courses and one on content; if one, content only) and would take approximately 10 minutes to administer. Student names/IDs are NOT asked and no grade need be assigned. I would be present to administer the survey and to ask for volunteers for later interviews.

I would very much appreciate your consideration in allowing me a precious few minutes of your first class period on August 25 or 26. I would be happy to provide additional information about my project if you are interested or if it helps in your decision.

Thank you,

Janelle Bailey

Spring 2004

Dear Professor,

I would like to ask a few moments of your time. My dissertation work is on students' understanding of star formation. In order to support this work, I would like to survey your general education courses (NATS 102) on the **first** day of class and **again** during the last week of class. Because we hope to look at pre-instructional understanding, it is imperative that the first survey be administered **before any instruction take place**; we have more flexibility at the end of the semester, however.

The survey has three questions (one on prior astronomy courses and two content questions about stars) and would take approximately 10 minutes to administer. Student names are requested so that I may match responses from the beginning and end of the semester. No grade need be assigned, although if you want to know for your own records who responded, I am happy to provide this information. I will be present to administer the survey and to ask for volunteers for later interviews.

I would very much appreciate your consideration in allowing me a precious few minutes of your first class period on January 14 or 15. I would be happy to provide additional information about my project if you are interested or if it helps in your decision. Please let me know of your decision to participate in this research project as soon as possible so that I may make the necessary arrangements to support you and your students.

Thank you very much for your time,

Janelle Bailey

Fall 2004

Dear Professor,

I would like to ask a few moments of your time. My dissertation work is on students' understanding of star formation. In order to support this work, I would like to survey your general education courses (NATS 102) on the **first** day of class and **again** during the last week of class. Because we hope to look at pre-instructional understanding, it is imperative that the first survey be administered **before any instruction take place**; we have more flexibility at the end of the semester, however.

The survey has three questions (one on prior astronomy courses and two content questions about stars) and would take approximately 10 minutes to administer. Student names are requested so that I may match responses from the beginning and end of the semester. No grade need be assigned, although if you want to know for your own records who responded, I am happy to provide this information. I will be present to administer the survey and to ask for volunteers for later interviews.

I would very much appreciate your consideration in allowing me a precious few minutes of your first class period on August 23 or 24. I would be happy to provide additional information about my project if you are interested or if it helps in your decision. Please let me know of your decision to participate in this research project as soon as possible so that I may make the necessary arrangements to support you and your students.

Thank you very much for your time,

Janelle Bailey

APPENDIX B

STUDENT-SUPPLIED RESPONSE (SSR) SURVEY QUESTIONS (PHASE I)

Form	Item(s)
Spring 2003	
A	Describe what you think a star is.
B	Describe where you think stars come from.
C	Describe how you think a star is formed.
Fall 2003	
D	Have you ever taken an astronomy course before the one in which you are in now? (yes/no) Describe the process by which you think a star is formed. Support your answer with a sketch and labels, if possible.
E	Have you ever taken an astronomy course before the one in which you are in now? (yes/no) List all of the things that you think are present and/or will occur when a star forms.
F	Have you ever taken an astronomy course before the one in which you are in now? (yes/no) We see stars because they give off light (energy). Describe how you think this happens.
Spring 2004	
G	1. Have you ever taken an astronomy course before the one in which you are in now? (yes/no) 2. Describe what you think a star is. Support your answer with a sketch and labels, if possible. 3. We see stars because they give off light (energy). Describe how you think the light (energy) is created inside and/or on the surface of the star. Support your answer with a sketch and labels, if possible.

-
- H
1. Have you ever taken an astronomy course before the one in which you are in now? (yes/no)
 2. Describe the process by which a star is formed. Support your answer with a sketch and labels, if possible.
 3. Are all stars the same? Indicate 'yes' or 'no' below and answer the accompanying question. Support your answer with a sketch and labels, if possible.
Yes _____ In what way(s) are all stars the same?
No _____ In what way(s) are stars different?
- J
1. Have you ever taken an astronomy course before the one in which you are in now? (yes/no)
 2. Is there a difference between a star and a planet? Indicate 'yes' or 'no' below and answer the accompanying question. Support your answer with a sketch and labels, if possible.
Yes _____ Describe what you think the differences are.
No _____ Describe why you think they are the same.
 3. We see stars because they give off light (energy). Describe how you think the light (energy) is created. Support your answer with a sketch and labels, if possible.
- K
1. Have you ever taken an astronomy course before the one in which you are in now? (yes/no)
 2. Describe what you think a star is. Support your answer with a sketch and labels, if possible.
 3. Are all stars the same? Indicate 'yes' or 'no' below and answer the accompanying question. Support your answer with a sketch and labels, if possible.
Yes _____ In what way(s) are all stars the same?
No _____ In what way(s) are stars different?
 4. We see stars because they give off light (energy). Describe how you think the light (energy) is created inside and/or on the surface of the star. Support your answer with a sketch and labels, if possible.
-

Fall 2004

- L
1. Have you ever taken an astronomy course before the one in which you are in now? (yes/no)
 2. We see stars because they emit energy. Describe how you think this energy is created.
 3. Other than appearing to move quickly across the sky, how is a *shooting star* different from a *star*?
-

-
- M
1. Have you ever taken an astronomy course before the one in which you are in now? (yes/no)
 2. Why do some stars appear brighter than others?
 3. Your friend tells you that a shooting star is the result of a star running out of fuel and “burning out.” Do you agree or disagree with your friend? Explain why you think the statement is correct or incorrect.
- N
1. Have you ever taken an astronomy course before the one in which you are in now? (yes/no)
 2. Why do some stars appear different colors?
 3. Your friend tells you that a shooting star is the result of a star running out of fuel and “burning out.” Do you agree or disagree with your friend? Explain why you think the statement is correct or incorrect.
-

APPENDIX C

REQUEST FOR INTERVIEW VOLUNTEERS (PHASE I)

Fall 2003

To be read to general education science courses:

Good morning. My name is Janelle Bailey and I am inviting your voluntary participation in an interview project. The project is being used to determine the range of students' knowledge about concepts in science for the purposes of determining the initial ideas students bring to general science courses.

I am in need of several students who would be willing to be interviewed about their beliefs and understandings about astronomy. Interviews will be scheduled at your convenience and will last between 30 and 90 minutes. Each volunteer will be asked to participate in one interview.

Your decision to volunteer for this project or not will in no way impact your course grade. There are neither perceived risks nor benefits for your participation. You will receive no compensation and will be asked to contribute nothing other than the time for an interview.

If you are interested in being interviewed for this project, please see me at the end of this announcement to work out the details.

Thank you for your time.

APPENDIX D

SEMI-STRUCTURED INTERVIEW QUESTIONS (PHASE I)

Volunteers were interviewed in a conference room on campus at a time agreed upon by the volunteer and the researcher(s). The questions below were used as guides to conduct the interview. Volunteers were frequently asked to explain or elaborate upon their response. Depending upon the responses, questions might have been asked in an order different than their presentation below. Interviews were audiotaped and transcribed by the researcher.

Fall 2003, Set 1

BACKGROUND ABOUT STUDENT

- Please tell me about your background in science, such as describing any science classes you have taken or any informal science interests that you have pursued.
- Have you been taught anything about stars? Please describe the lesson/context/situation as best you can remember.
- Do you remember which question you answered for the survey that we did in class?
- Do you remember what you said (about, doesn't have to be word for word)?

PROPERTIES

- Tell me what you think a star is.
- How did it (the star) end up that way?
- Could you show me what it looked like before it was a star?
- Show me another picture of an in-between time (between your last picture and when it is a star)

MAKE COMPARISONS

- Is a star different from a planet? How so/why not?
- Is the Sun the same thing as a star? Why/why not?

FORMATION/CREATION

- How do you think the stars came to exist or were created?
- Do you think stars are still being created now? Why/why not?
- Do you think stars can still be created in the future? Why/why not?

TRYING TO GET AT 'GRAVITY' (START WITH BALL OF GAS TYPE OF RESPONSE)

- Would the gas stay together (maintain shape) if it were in this room? (What keeps it together?)

- Balloon example – why doesn't the gas of a star go all over the place like the gas of a balloon when it is let out

TRYING TO GET BEYOND 'GAS', MAYBE TO 'PLASMA'

- How hot is a star?
- Density of a star versus a planet – teaspoon example.
- Define gas, define plasma

TRYING TO GET AT 'FUSION'

- I can see light from the Sun/a star. How does that happen?
- How is the light made/where does it come from?
- Is it a chemical process, like you might have studied in HS Chemistry?

IF THEY TALK ABOUT FIRE OR BURNING...

- Burning – is it the same kind of burning as in a campfire or on a gas stove?
- What started the fire/burning?
- Does it have flames?
- Is it a chemical process, like you might have studied in HS Chemistry?

Volunteers were interviewed in a conference room on campus at a time agreed upon by the volunteer and the researcher(s). The questions below were used as guides to conduct the interview. After the first few interviews (Set 1), some additional questions were created for Set 2. The new questions were based upon student responses in Set 1, where students provided information that was interesting enough that the researchers wanted to ask the question of other students. Volunteers were frequently asked to explain or elaborate upon their response. Depending upon the responses, questions might have been asked in an order different than their presentation below. Interviews were audiotaped and transcribed by the researcher.

Fall 2003, Set 2

BACKGROUND ABOUT STUDENT

- Please tell me about your background in science, such as describing any science classes you have taken or any informal science interests that you have pursued.
- Have you been taught anything about stars? Please describe the lesson/context/situation as best you can remember.
- Do you remember which question you answered for the survey that we did in class?
- Do you remember what you said (about, doesn't have to be word for word)?

PROPERTIES

- Tell me what you think a star is.
- How did it (the star) end up that way?
- Could you show me what it looked like before it was a star?
- Show me another picture of an in-between time (between your last picture and when it is a star)

MAKE COMPARISONS

- Is a star different from a planet? How so/why not?
- Is the Sun the same thing as a star? Why/why not?

FORMATION/CREATION

- What was in that spot (where the star is now) before the star?
- How do you think the stars came to exist or were created?
- Do you think stars are still being created now? Why/why not?
- Do you think stars can still be created in the future? Why/why not?

TRYING TO GET AT 'GRAVITY' (START WITH BALL OF GAS TYPE OF RESPONSE)

- Would the gas stay together (maintain shape) if it were in this room? (What keeps it together?)
- Balloon example – why doesn't the gas of a star go all over the place like the gas of a balloon when it is let out

TRYING TO GET BEYOND ‘GAS’, MAYBE TO ‘PLASMA’

- How hot is a star?
- Density of a star versus a planet – teaspoon example.
- Define gas, define plasma

TRYING TO GET AT ‘FUSION’

- I can see light from the Sun/a star. How does that happen?
- How is the light made/where does it come from?
- Is it a chemical process, like you might have studied in HS Chemistry?

IF THEY TALK ABOUT FIRE OR BURNING...

- Burning – is it the same kind of burning as in a campfire or on a gas stove?
- What started the fire/burning?
- Does it have flames?
- Is it a chemical process, like you might have studied in HS Chemistry?

END STATES

- Now there’s a star, what happens next?
- Does the star stay the same forever? If not: How would you describe the changes incurred over time? Would it become something different? Describe.
- Would it get XX or XX (from when it initially forms)?
 - Bigger or smaller (find biggest or smallest point, then what happens next)
 - Hotter or colder (does it keep temp gradient if described earlier, e.g., layers)
 - More/less energy output
 - Brighter/dimmer
 - Higher/lower pressure

TYPES OF STARS

- Sometimes astronomers talk about different types of stars. Have you ever heard of any names or types that you could tell us about? Describe/explain what you think.
Could provide
 - Red giant
 - White dwarf
 - Supernova
 - Neutron star??

APPENDIX E

INTERVIEW SUMMARIES (PHASE I)

The following are summaries of the seven interviews conducted during the Phase I, presented in chronological order of the interview. All names are pseudonyms. The participants are:

1. *Emma*
2. *Steven, with sketch*
3. *Charlie*
4. *Katie*
5. *Sam, with sketch*
6. *Julie*
7. *Carla, with sketch*

Summary of Interview with “Emma” on September 8, 20003, 2pm

The first interview was with Emma, a freshman. She had not had any astronomy before the class in which she was enrolled, although she had studied some related topics (such as light) in her physics and chemistry courses in high school. Emma remembered responding to a “how stars form” survey question, although she didn’t feel like she had a very good answer. She remembered seeing pictures of star-forming nebula from magazines. Near the end of the interview she said that she felt like stars probably were not going to continue to form, although some may still be going through the “coming together” stage (see below).

She described stars as “very massive” and that our Sun is one example of a smaller star. Differences in size and temperature were acknowledged, as were the possibility of stars harboring planetary systems. She chose not to draw any pictures to support her responses.

She recognized that stars give off radiation (light) and possibly “other types of energy.” Emma had some confusion about whether radiation is a type of energy, or something different. She is able to differentiate between visible light and other types, such as what plants use in photosynthesis [UV] and what is felt as heat [IR]. She was able to list several types of energy and stated that it “makes things do work.” When asked how “stars end up like that” (referring to their giving off light), Emma replied that she thought there were chemical reactions occurring on the surface. She mentioned energy conservation, and so used throughout the interview the idea that the energy already exists

within the star. There is no discussion of how it is created. Likewise in one place she mentions that matter “always existed” and relates it to the Big Bang, although little detail is given. Chemical reactions were again discussed later in the interview when asked directly where a star’s light comes from.

In discussing the formation process, Emma was able to describe that gravity pulls matter together. In a later part of the interview, she describes an analogy to water droplets joining together to make larger drops. She said “everything has gravity but bigger things have bigger gravity.” Eventually this was clarified to mean that gravity is dependent upon mass more so than physical size. Gravity was again discussed later when asked if gases also have gravity (“it’s still matter, so, so it would still have a bit...”)

When asked to compare a star with a planet, Emma’s first response related to the energy released by stars (whereas planets cannot do this). Later she said that planets only reflect sunlight, whereas stars emit light. She felt the two objects were probably made of the same materials, and mentioned the periodic table (but no specific elements). She noted that it might be possible to have a very small star, similar in size to Jupiter, but that “in the solar system, our Sun is considerably bigger,” and that stars would be more massive. Density was not discussed. Emma also noted that she thinks of stars as gaseous whereas planets are solid; she specifically said she has difficulty understanding the gas giant planets. Later she distinguished that asteroids were also different from stars – asteroids are “like a rock.”

Early in the interview she said that she had often heard the phrase “ball of gas” used when describing stars. She felt that stars must be very hot in order to have the

elements be in the gas phase. The material might be similar to extremely hot lava. When asked directly about temperatures, she felt that a star's temperature would be several hundreds of thousands of degrees, and that it would be hotter in the center and cooler toward the surface. She said that this idea was based on the notion that flames have hotter temperatures near the base, although she was not sure where this idea came from. She did not seem to think the star is on fire, but that flares might be small explosions on the star's surface.

Although Emma volunteered certain descriptions based upon the surface of the star, she admitted that she hadn't really thought about what might be happening in the interior of the star. For example, she was not confident about whether the interior or core of the star would still be gas or might instead be solid.

Summary of Interview with “Steven” on September 8, 2003, 4pm

Steven was our second interviewee. A freshman, Steven had no formal astronomy courses in the past but was very interested in science. He had previously read books such as *A Brief History of Time* (Stephen Hawking) and soon proved himself very knowledgeable about astronomical phenomenon. Early in the interview he was able to draw a picture to support his ideas; see Figure E-1.

Steven remembered receiving the survey which asked him to describe the formation process of a star. He then proceeded to describe the process fairly well, including the gravitational collapse of a cloud of matter, a subsequent increase in pressure, and then the start of hydrogen fusion and the emission of energy. Although no specific time scale was discussed, Steven said the process would occur “over a long period of time.” He believed the primary elements present in a star are the “lighter, simpler ones” like hydrogen, helium, and lithium, although he referred only to hydrogen when discussing fusion.

The nature of gravity was not discussed in the same manner as it was with Emma, although Steven appeared to be more comfortable with the concept than Emma was. He quickly identified that gravity is dependent upon mass, although he made no mention of its distance dependence. The gravitational collapse, he responded when asked, was likely triggered by “some kind of external force.” Steven felt the collapse would be driven by density variations throughout the gas cloud, where the gravitational pull would be stronger from the denser regions.

Upon an interviewer's prompting, Steven attempted to define pressure, a term he had used in his original description of the formation process. The explanation related very closely to density and to the kinetic energy of the individual particles, and he said that when there is an "increase [in] the overall energy, that's going to increase the pressure." He was also able to discuss temperature when asked about other physical characteristics that might describe the star, stating that the temperatures of stars are likely in the millions of degrees at the center and tens of thousands on the outside.

The last key area that Steven discussed was the process of fusion. He recognized that this process can only occur with extremely high temperatures and pressures, and that those conditions are most likely to exist at the center of the star. He described fusion as the creation of a new element (helium) after the collision of hydrogen atoms when the protons are fused. The process was simplified, in that it simply took two protons from hydrogen atoms to create a helium atom (compare this to the actual fusion process, which actually requires additional steps). Energy is released as a result of the collisions, in the various wavelengths of light, although Steven is unclear about exactly where the energy comes from. He also felt that fission, where heavier elements are broken apart through collisions, was also taking place – fusion near the center and fission in the outer areas of the star. He did not think chemical reactions, especially combustion, would occur in a star.

Steven was confident that our Sun is just an example of a normal star and that all stars are created through this same process. He mentioned specifically red giants and white dwarfs, but clarified that these are things that happen later in the star's lifetime.

“Stars are pretty much always going through a cycle,” he said, so the continuing process of stellar formation was a belief that he had. When discussing the differences between stars and planets, he focused primarily on the composition – that terrestrial planets such as Earth have many more heavy elements. He did not address other characteristics (such as mass, radius, or temperature) or processes such as fusion as they relate to planets.

Figure E-1. Sketch from Steven, drawn during his interview.

Summary of Interview with “Charlie” on September 9, 2003, 3:30pm

Charlie was a freshman who was planning to major in history. He had a fairly strong science background, including courses through the International Baccalaureate program. He did not remember which survey question he received or what he might have responded, and he did not draw any pictures during the course of the interview.

The interview began in earnest by asking Charlie what a star is. He described a star as an “extremely hot, dense ball of gases that... [are] in the process of fusion.” He added that a star would also have a “gravity field” around it. He felt that hydrogen was probably the most common element present, and that not all elements seen on the periodic table would be present. No other elements were named. Elaboration on his original answer revealed that Charlie believed the temperature to decrease from the core to the outside, but he wasn’t sure about the exact temperature beyond a guess of “millions of degrees.”

Another characteristic that Charlie discussed in some detail was pressure. We did not pursue this definition as we had with Steven. Charlie felt that the pressure would create physical changes in the elements of the star; in particular, he thought the density would increase closer to the center of the star.

When asked what existed before the star, Charlie identified and later defined a nebula. His description of the formation process focused at first on the density and pressure of the gasses coming together, but responded when asked that “the gravity field in the area” might cause the elements to be drawn together. He recognized that stars have

different ages and are continuing to be formed now and into the future. He also suggested that stars have a death process, although this line of thought was not pursued further.

The definition of gravity was not explored in detail, although Charlie eventually said that the amount of gravity would depend upon the mass of particles present. He tended to speak in terms of fields and wells, although these were not defined. It is gravity, he explained, that keeps the gases together (compared to the skin of a balloon).

In the original description of a star, Charlie said it was “in the process of fusion.” Later in the interview we discussed this idea in more detail. He suggested that the high temperatures allow electrons to be “stripped away from the element” and that this allowed the element to fuse with other things. He suggested that fusion requires high temperatures and pressures, and accordingly probably occurs only near the center of the star and not toward the outside. There was no discussion of nuclear reactions or the creation of energy. Light was described as created from energizing particles (perhaps analogous to electron transitions?) so that they give off photons.

As with the prior interviews, we asked whether a star and a planet are the same types of object. Charlie was the first student to suggest that these might be the same, “on different ends of the spectrum.” He did differentiate via some physical characteristics, such as size and pressure. He also said that stars would give off more energy. He also discussed the molten cores found in planets, and suggested that stars are more massive and denser than planets.

Summary of Interview with “Katie” on September 11, 2003, 1pm

Like the other students before her, Katie was a freshman. Although she had no prior astronomy instruction, she vaguely remembered discussing stars in her junior high courses. She did not draw any pictures during her interview.

Katie began by describing a star simply as a ball of gas. With some prompting, she added some additional detail. For example, she said that stars “can vary in size and color,” although there was some confusion on if and how these two characteristics related to one another. She also said that she thought stars were “pretty hot,” later suggesting that they might be in the thousands of degrees. She thought the star would be hotter in the center and seemed to remember hearing that sunspots were hotter than the rest of the Sun.

Katie felt like there would be motion involved in stars, and discussed two different types. She first felt like the star’s materials “mixes up” as evidenced by seeing differences in the Sun (e.g., sunspots). She also indicated that stars orbit the galaxy and that the galaxy moves through the universe. Later she indicated that the motion of molecules, and the resulting friction from their collisions, might be the source of energy that creates the light that we observe.

Like most of the students before her, Katie felt stars and planets are different objects; in elucidating those differences, she focused only on a few physical differences. She said that planets can be solid (although not all are) and stars are gas. She also said “planets are more mass” and later said that she meant “matter” instead of mass. She did

not know what kind of gas would be in a star, but did not think it would be the same as the air we breathe.

Gravity came up only briefly, approximately mid-way through the interview. Katie knew that gravity pulled the gas together to create a star, but did not elaborate on what she meant by this. When asked to compare what would happen to a balloon if its skin burst (to the gas of a star), she suggested that the star's gas would not spread out because of "the lack of atmosphere in space... there's no oxygen in space." She felt that the air in a balloon would diffuse throughout the room if it burst in the room.

Summary of Interview with “Sam” on September 25, 2003, 11:15am

The fifth interview with Sam, a mechanical engineering major, began with technical difficulties. The audiotape stopped recording as the interviewer asked the second question, probably relating to Sam’s background knowledge in science. The summary of this portion of the interview is therefore reconstructed from notes rather than the transcript. The problem was detected and the audiotape replaced partway into the content as Sam was talking about star formation; he also drew a picture of this process (see Figure E-2). Additional auditory problems (i.e., it was hard to hear Sam when he spoke while drawing) appeared in various portions of the interview.

Sam responded that stars are formed when matter is pulled together by gravity. The matter that exists is “the building blocks of life,” such as carbon, hydrogen, and oxygen. Once gravity has pulled the matter together, it is compressed and gives off heat and starts to burn. Sam felt this process would take millions to billions of years. As he described the process, he recognized that the star would not be on fire in the conventional sense, but rather “this is more a heat that’s radiated by the compression of the matter.” Fusion is not mentioned to this point.

When asked about the differences between stars and planets, Sam described an evolutionary process that includes the names of different stages (although he didn’t remember the order). He said it was reasonable to think that stars would evolve into planets. Sam felt that planets are more dense than stars, but that the Sun is hotter than all of the planets within our Solar System, with possible temperatures ranging from “as cold

as space” to millions of degrees. Sam indicated that there could be reactions between elements at the center of the star, but was unable to be more specific. He said that stars would be hotter on the inside and cooler near the outside, and that energy was given off primarily from the center of the star.

Sam next talked about the future of stars – how they might evolve and eventually stop emitting energy. Different possibilities were described, including that stars might “burn out” (stop giving off energy) or eventually explode. The amount of matter initially present may be the cause of different evolutionary tracks. Sam also indicated that in the case of red giants, which are “puffed up” stars that have expanded, their density would be less than it had been before the expansion. Some tracks also have periods where one particular element – oxygen, for example – is being burned more than others, and so would dominate the star’s spectrum. He also describes supernova as a large, fast explosion that leaves behind dust particles.

Figure E-2. Sketch from Sam, drawn during his interview.

Summary of Interview with “Julie” on September 25, 2003, 1pm

Julie is a musical theater major with at least one previous semester at this institution (she did not indicate her class standing, but had taken an ES 101 course previously). She indicated that she had “the basics” in high school – biology, chemistry, and physics – but no astronomy courses. Her father is a computational chemist who works for NASA (at Ames Research Center), but Julie indicated that she is not inclined toward an interest in science. She did not make any drawings during the interview.

When asked to define a star, Julie immediately said that she thought it is “a ball of burning gas.” She proceeded to describe differences among stars, such as color and temperature (with white being the hottest), and said that they will eventually blow up. She suggested that stars might be made of hydrogen and possibly helium, but that it might depend upon the star.

Julie also indicated that stars are significantly bigger than Earth (“like a million times bigger”). In further comparisons, she indicated that the Sun would be “not solid” and hotter than Earth (millions of degrees), with the center being hotter than the outer parts. In talking about the temperature difference, she used the layers of Earth as a model for her ideas about the Sun. Later in the interview she indicated that a “scoop” of Earth would weigh more than one of the Sun, because Earth is solid.

She didn’t immediately have a good idea of how the Sun came to exist. With the help of a balloon analogy (the rubber balloon keeps the gas particles together), Julie indicated that maybe gravity keeps the gas particles together in a star, or that maybe

something about the structure of the gas particles themselves did it, like the bonds keeping hydrogen and oxygen together in a water molecule.

Upon clarification of her use of the word “burning,” Julie indicated that the star simply gives off a lot of energy – that fire could not take place because of the lack of oxygen. She suggested that the reason for the large amount of heat given off by the Sun was the motion of the gas particles. The motion of the particles was also, she thought, the source of the light that we see with our eyes.

Julie knew that the Sun is a star, and that it is the closest star to Earth. She agreed with a review of her earlier comment that white stars are the hottest and red the coolest, and indicated that white stars would live shorter lifetimes than red stars (“I think that white stars burn out a lot faster.”) White stars were also thought to be brighter than red ones. She indicated earlier in the interview that the Sun is orange-ish in color, and later indicated that stars can fall anywhere on a continuum of colors that has white at one end and red at the other. The lifetimes she suggested were on the order of billions of years.

When prompted, Julie said that stars could either “go supernova” (explode) or simply “burn out – just die.” She was unclear on what would cause an explosion, but indicated that some sort of instability in the star might be the cause. She also indicated, after talking through the possibilities, that the Sun (or another star which “burned out”) would not remain the same over its life in terms of temperature or energy output. Julie also said that when the Sun stopped emitting energy, the planets might be “sucked in” or fly off into space, later sticking with the “sucked in” idea and saying that gravity would get stronger when the Sun burned out. However, upon further questioning, she

recognized a conflict between the idea of gravity and her idea of planets no longer orbiting – “the gravity *can’t* get that much stronger, then, because obviously some of the planets fly off.”

Julie then said that stars could also become black holes – where the star collapses and even light cannot escape – but didn’t know “where that fits in” to the discussion. Upon further questioning, she thought that the different outcomes (burn out, supernova, black hole) might be the result of how much energy the star was giving off earlier in its lifetime, although it is *not* related to brightness. She did not explain the difference between energy and brightness.

When asked, Julie said she had heard of red giants and white dwarfs, but not neutron stars. She thought these might all be different types of stars, and added that she had also heard of brown dwarfs.

Summary of Interview with “Carla” on September 29, 2003, 2pm

The ASTRO 101 course was Carla’s first at the university. In high school she had taken biology (freshman-level and AP), chemistry, and physics, but no high school. She sometimes sailed with her father, and witnessed him using the stars to help him navigate at night, but otherwise didn’t feel she knew much about stars.

When defining a star, Carla said that it was gas and dust that had been pulled together by gravitational forces and is now burning. She thought that the gravity that pulled this material together was related to gravity on Earth (which pulls things *down* rather than together), but somehow different. She also said that other forces beside gravity might act to help hold the gases together. When asked about how the star formed, she said that she thought the material (sometimes using the word objects) was spread out, farther apart, until it was pulled together by something. The gases she said would be in the star were things like oxygen and nitrogen (“not petroleum gas, you know, or gas they use in cars, not that type of gas.”) As the materials start to come together, they orbit around a central area and begin to “spin” faster.

Carla indicated that all stars are different from one another, in composition, size, and shape. When asked to compare stars to planets, she said that planets are “more structured,” and indicated the layers of Earth as a possible example of the structure of planets. She also said that planets are “more stable,” in that a planet is less likely to explode or burn up in the way that stars can. She said that stars are likely “more solid” in the center but that there is no discernable surface in the way that there is for Earth. She

said that while “overall” stars and planets are made of the same types of material, they may not be put together in the same way – leading to overall composition differences. Although she at first said stars are bigger than planets, she followed up by indicating that we haven’t seen all stars or planets to know for sure. Stars, she said, are hotter than planets, but planets are denser. When asked if the Sun was the same as other stars, she said, “I think that there are so many different variations of stars that they’ve been... it’s like animals, you know, they’ve been categorized into animal kingdom.”

When trying to quantify the differences between stars and planets, Carla said that stars would typically be “thousands and thousands” of times bigger than planets, as well as tens of thousands of degrees Fahrenheit. The star might be hotter in the center, “*at least* tens of thousands of degrees.”

Carla said that she had heard of different types of stars, such as red giants and brown dwarfs, but didn’t know any details about either type. She indicated that stars could go from one type to another, but that all eventually explode.

When asked to further explain her idea of the star emitting light because it is burning, she said that it wasn’t flames but rather, “I think that the actual star is just so hot that it creates energy which is turned into light.” Although she thought this process might have something to do with the motion of pieces of the star or friction, she was unclear about the details. She also said that the light would be created from all parts of the star.

Carla said that the Sun must have lived for billions of years, in order to match the age of Earth. She also described that light can take time to travel, so that the light you see actually came from the past. When asked about what will happen to the Sun, Carla said it

will “blow completely out of proportion and, like, toast every planet in our solar system and then shrink into this tiny little dot.” As it at first expands to get bigger, it would get cooler and dimmer. Eventually it shrinks back down, getting smaller than it started. When prompted about her use of the word “explosion” in describing the fate of stars, she said that this expansion and shrinking process was what she meant, as the result of having too much energy that therefore had to be released in some way.

Figure E-3. Sketch from Carla, drawn during her interview.

APPENDIX F

RECRUITMENT LETTERS TO GENERAL EDUCATION PROFESSORS (PHASE II)

Spring 2005 – to ASTRO 101 instructors

December 17, 2004

Dear Instructor,

I would like to ask a few moments of your time. My dissertation work is on nonscience majors' understanding of the properties of stars and the process of star formation. Your students' ideas are the primary source of data for this work, which will later inform instruction and curriculum development on this topic

In order to support this work, I would like to administer a short survey to your general education (NATS 102) students on the first day of class and again during the last week of class. Because we hope to look at pre-instructional understanding, it is imperative that the first survey be administered before any instruction take place; we have more flexibility at the end of the semester, however.

There are 12 different versions of the survey, in 3 different formats. The different versions would be randomly distributed to the students in your class. It is expected to take approximately 15 minutes to administer. Student names are requested so that I may match responses from the beginning and end of the semester.

I would very much appreciate your consideration in allowing me a precious few minutes of your first class period on January 12 or 13. I would be happy to provide additional information about my project if you are interested or if it helps in your decision. Please inform me of your decision to participate in this research project as soon as possible so that I may make the necessary arrangements to support you and your students.

Thank you very much for your time,
Janelle Bailey

Spring 2004 – to ES 101 instructors

December 20, 2004

Dear Instructor,

I would like to ask a few moments of your time. My dissertation work is on nonscience majors' understanding of the properties of stars and the process of star formation. This work will later inform instruction and curriculum development on this topic. Because I anticipate that your course is comprised of students similar to those in the introductory astronomy classes, but does not include instruction on this topic, I would like to survey your students as a **control group**.

In order to support this work, I would like to survey your general education courses (NATS 101 or 104) on the **first** day of class and **again** during the last week of class. Because we hope to look at pre-instructional understanding, it is imperative that the first survey be administered **before any instruction take place**; we have more flexibility at the end of the semester, however.

There are 12 different versions of the survey, in 3 different formats. The different versions would be randomly distributed to the students in your class. It is expected to take approximately 20 minutes to administer. Student names are requested so that I may match responses from the beginning and end of the semester.

I would very much appreciate your consideration in allowing me a precious few minutes of your first class period on January 12 or 13. I would be happy to provide additional information about my project if you are interested or if it helps in your decision. Please inform me of your decision to participate in this research project as soon as possible so that I may make the necessary arrangements to support you and your students.

Thank you very much for your time,
Janelle Bailey

Fall 2005 – to ASTRO 101 instructors

July 18, 2005

Dear Instructor,

I would like to ask a few moments of your time. My dissertation work is on nonscience majors' understanding of the properties of stars and the process of star formation. Your students' ideas are the primary source of data for this work, which will later inform instruction and curriculum development on this topic.

In order to support this work, I would like to administer a short survey to your general education (NATS 102) students on the first day of class and again during the last week of class. Because we hope to look at pre-instructional understanding, it is imperative that the first survey be administered before any instruction take place; we have more flexibility at the end of the semester, however.

The survey is expected to take approximately 15 minutes to administer. Answers will be completed on a scannable form that I will provide. Student names and ID's are requested so that I may match responses from the beginning and end of the semester.

I would very much appreciate your consideration in allowing me a precious few minutes of your first class period on August 22 or 23. I would be happy to provide additional information about my project if you are interested or if it helps in your decision. Please inform me of your decision to participate in this research project as soon as possible so that I may make the necessary arrangements to support you and your students.

Thank you very much for your time,
Janelle Bailey
Ph.D. Candidate

Fall 2005 – to ES 101 instructors

July 15, 2005

Dear Instructor,

I would like to ask a few moments of your time. My dissertation work is on nonscience majors' understanding of the properties of stars and the process of star formation. Your students' ideas are the primary source of data for this work, which will later inform instruction and curriculum development on this topic. Because I anticipate that your course is comprised of students similar to those in the introductory astronomy classes, but does not include instruction on this topic, I would like to survey your students as a control group.

In order to support this work, I would like to administer a short survey to your general education (NATS 101 or 104) students on the first day of class and again during the last week of class. Because we hope to look at pre-instructional understanding, it is imperative that the first survey be administered before any instruction take place; we have more flexibility at the end of the semester, however.

The survey is expected to take approximately 15 minutes to administer. Answers will be completed on a scannable form that I will provide. Student names and ID's are requested so that I may match responses from the beginning and end of the semester. Each student will be randomly assigned a generic ID number after the pre- and post-course surveys have been matched.

I would very much appreciate your consideration in allowing me a precious few minutes of your first class period on August 22 or 23. I would be happy to provide additional information about my project if you are interested or if it helps in your decision. Please inform me of your decision to participate in this research project as soon as possible so that I may make the necessary arrangements to support you and your students.

Thank you very much for your time,
Janelle Bailey

APPENDIX G

STAR FORMATION CONCEPT INVENTORY, VERSION 1 (3 FORMATS)

All versions and formats of the concept inventory began with a page similar to the following. This page will not be repeated for subsequent versions in the Appendices.

Name _____

Star Formation Concept Inventory

Version 1a-1

Instructions: circle the best answer for each question.

**There are 18 questions total (#1-15 and 31-33),
printed on both the front and back of the paper.**

Star Formation Concept Inventory
Version 1a

Version 1a was divided into two different forms. Each form had questions #31-33 plus 15 of the 30 questions.

1. What is a star?
 - a. a substance which gives off light at night
 - b. a round hot body of gaseous material
 - c. a point in the sky which gives off light
 - d. a ball of burning gas

2. Compared to the Sun, the greatest energy output (brightness) a star will ever have is
 - a. 10 – 100 times greater
 - b. 100 – 1,000 times greater
 - c. 1,000 – 10,000 times greater
 - d. 10,000 – 100,000 times greater
 - e. more than 100,000 times greater

3. In an average star, gravitational collapse is balanced by
 - f. churning of stellar material into and out of the core.
 - g. photon pressure produced during fusion.
 - h. solid material at the stellar core.
 - i. mass ejected during fusion.
 - j. interior cooling of the star.

4. Which fundamental property determines all characteristics and future events of a star's life?
 - a. mass
 - b. temperature
 - c. size (diameter)
 - d. color
 - e. distance from Earth

5. How is the lifetime of a star related to its mass?
 - a. More massive stars live considerably longer lives than less massive stars.
 - b. More massive stars live considerably shorter lives than less massive stars.
 - c. More massive stars live slightly shorter lives than less massive stars.
 - d. More massive stars live slightly longer lives than less massive stars.
 - e. All stars have the same lifetimes regardless of mass.

6. What is the name given to a star as it is initially forming?
 - a. protostar
 - b. main sequence star
 - c. supernova
 - d. red giant
 - e. white dwarf

7. In the future the Sun will
 - a. use up all its 'fuel' and will eventually stop shining.
 - b. explode as it burns out of control.
 - c. continue to shine because it has an endless reserve of fuel.
 - d. continue to shine because it has a renewable supply of fuel.

8. The light from stars that we see on Earth results from
 - a. reflection of sunlight.
 - b. chemical reactions inside the stars.
 - c. nuclear reactions inside the stars.
 - d. burning of material inside the stars.
 - e. burning on the surfaces of the stars.

9. The range of temperatures for average stars is
 - a. 300 – 3,000 K
 - b. 300 – 30,000 K
 - c. 3,000 – 30,000 K
 - d. 30,000 – 300,000 K
 - e. 300,000 – 3,000,000 K

10. If a red star and a blue star both have the same size (diameter) and both are the same distance from Earth, which one looks brighter in the sky?
- a. the red star
 - b. the blue star
 - c. same, because they are the same distance from Earth
 - d. same, because they are the same distance from Earth and the same size (diameter)
 - e. same, because they are the same distance from Earth, size (diameter), and temperature
11. Which of the following is correct about the nature of planets and stars?
- a. Planets orbit around the Sun. Stars don't move.
 - b. Planets orbit around the Sun but stars move through space.
 - c. Planets and stars both orbit the Sun.
12. Star A has a lifetime of 50 million years, while star B has a lifetime of only 10 million years. What can you say about the masses of these stars?
- a. Star A has the greatest mass.
 - b. Star B has the greatest mass.
 - c. Stars A and B have approximately the same mass.
 - d. There is not enough information given to answer this question.
13. Which of the factors below does NOT influence how bright a star appears to us on Earth?
- a. shape
 - b. energy output
 - c. size (diameter)
 - d. temperature
 - e. distance
14. Stars begin life as
- a. a piece off of another star.
 - b. a cloud of gas and dust.
 - c. a very large, hot planet.
 - d. a matter in Earth's atmosphere.
 - e. an asteroid.

15. The hottest stars are what color?
- a. red
 - b. white
 - c. blue
 - d. none of these, because all stars are the same temperature
 - e. none of these, because all stars are the same color
16. Stars are made mostly of which element when they first form?
- a. helium
 - b. hydrogen
 - c. carbon
 - d. oxygen
 - e. silicon
17. The Sun is...
- a. a large planet
 - b. a hot planet
 - c. a small planet
 - d. an old planet
 - e. not a planet
18. Where does the Sun's energy come from?
- a. the combining of elements into new elements
 - b. radioactivity
 - c. the glow from molten rocks
 - d. heat left over from the Big Bang
 - e. heat left over from the Sun's formation
19. In which part of the Sun does nuclear fusion take place?
- a. photosphere
 - b. corona
 - c. core
 - d. radiative layer
 - e. nucleosphere

20. Star A has a mass of 2 solar masses and star B has a mass of 4 solar masses. How will the fusion rate of star A compare to the fusion rate of star B?
- Star A's fusion rate will be more than two times slower than that of star B.
 - Star A's fusion rate will be two times slower than that of star B.
 - Star A's fusion rate will be the same as that of star B.
 - Star A's fusion rate will be two times faster than that of star B.
 - Star A's fusion rate will be more than two times faster than that of star B.
21. Which of the following is correct about the nature of planets and stars?
- A planet makes its own light, but a star reflects sunlight.
 - A planet reflects sunlight, but a star makes its own light.
 - Both planets and stars make their own light.
 - Both planets and stars reflect sunlight.
22. Molecular clouds are
- clouds of simple molecules expelled by dying stars.
 - clouds that contain many complex molecules.
 - cool clouds of gas and dust.
 - hot, active clouds of molecular gas
23. Arrange the following stars by surface temperature from hottest to coldest: white stars, blue stars, and red stars.
- Hottest → Coldest
- red > white > blue
 - red > blue > white
 - white > red > blue
 - blue > white > red
 - blue > red > white
24. Star A has a mass of 5 solar masses and Star B has a mass of 10 solar masses. How will the total lifetime of Star A compare to the total lifetime of Star B?
- Star A's total lifetime will be less than half as long as that of Star B.
 - Star A's total lifetime will be half as long as that of Star B.
 - Star A's total lifetime will be the same as that of Star B.
 - Star A's total lifetime will be twice as long as that of Star B.
 - Star A's total lifetime will be more than twice as long as that of Star B.

25. The force that dominates the collapse of the gas and dust in a region that may eventually form a star is
- static electricity.
 - gravity.
 - magnetism.
 - friction.
 - nuclear fusion.
26. The property of stars that varies least is
- lifetime
 - mass
 - size (diameter)
 - temperature
 - energy output (brightness)
27. Compared to most stars, the Sun is
- very large.
 - average size.
 - very small.
 - not a star.
28. Stars A and B appear equally bright from Earth. However, star A actually gives off more light than star B. Which of the following is true about star A?
- It is the same distance from Earth as is star B.
 - It is farther away from Earth than is star B.
 - It is closer to Earth than is star B.
 - It has a smaller diameter than star B.
 - It is the same diameter as star B.
29. How does the Sun produce the energy that heats our planet?
- The gases inside the Sun are burning and producing large amounts of energy.
 - Hydrogen is combined into helium, giving off large amounts of energy.
 - Gas inside the Sun heats up when compressed, giving off large amounts of energy.
 - Heat trapped by magnetic fields in the Sun is released as energy.
 - The core of the Sun has radioactive atoms that give off energy as they decay.

30. Which of the following causes a star's interior temperature to increase during its formation?
- a. Nuclear fusion forces gravitational collapse, which generates a lot of heat.
 - b. Heat is generated when the star's gravity contracts.
 - c. Gravitational collapse involves the generation of heat from chemical reactions.
 - d. During collapse, gravitational potential energy is converted to heat.
31. Would you be willing to participate in a short interview to discuss your responses to this survey? NOTE: Indicating "yes" to this does not guarantee you will be selected to be interviewed, and if selected, you will still have the opportunity to refuse the interview.
- a. Yes
 - b. No
32. What is your gender?
- a. Female
 - b. Male
33. Have you had an astronomy course? (If you are taking this survey in an astronomy course, do NOT count it in your response.)
- a. Yes
 - b. No

Star Formation Concept Inventory
Version 1b

Version 1b was divided into four different forms. Each form had questions #31-33; remaining questions were divided between the forms (Version 1b-1, #1-8; Version 1b-2, #9-16; Version 1b-3, #17-23; and Version 1b-4, #24-30). Spacing has been reduced for inclusion here.

1. What is a star?
 - a. a substance which gives off light at night
 - b. a round hot body of gaseous material
 - c. a point in the sky which gives off light
 - d. a ball of burning gas

Explain the reasoning behind the choice you made.

2. Compared to the Sun, the greatest energy output (brightness) a star will ever have is
 - a. 10 – 100 times greater
 - b. 100 – 1,000 times greater
 - c. 1,000 – 10,000 times greater
 - d. 10,000 – 100,000 times greater
 - e. more than 100,000 times greater

Explain the reasoning behind the choice you made.

3. On an average star, gravitational collapse is balanced by
 - a. churning of stellar material into and out of the core.
 - b. photon pressure produced during fusion.
 - c. solid material at the stellar core.
 - d. mass ejected during fusion.
 - e. interior cooling of the star.

Explain the reasoning behind the choice you made.

4. Which fundamental property determines all characteristics and future events of a star's life?
- a. mass
 - b. temperature
 - c. size (diameter)
 - d. color
 - e. distance from Earth

Explain the reasoning behind the choice you made.

5. How is the lifetime of a star related to its mass?
- a. More massive stars live considerably longer lives than less massive stars.
 - b. More massive stars live considerably shorter lives than less massive stars.
 - c. More massive stars live slightly shorter lives than less massive stars.
 - d. More massive stars live slightly longer lives than less massive stars.
 - e. All stars have the same lifetimes regardless of mass.

Explain the reasoning behind the choice you made.

6. What is the name given to a star as it is initially forming?
- a. protostar
 - b. main sequence star
 - c. supernova
 - d. red giant
 - e. white dwarf

Explain the reasoning behind the choice you made.

7. In the future the Sun will
- a. use up all its 'fuel' and will eventually stop shining.
 - b. explode as it burns out of control.
 - c. continue to shine because it has an endless reserve of fuel.
 - d. continue to shine because it has a renewable supply of fuel.

Explain the reasoning behind the choice you made.

8. The light from stars that we see on Earth results from
- reflection of sunlight.
 - chemical reactions inside the stars.
 - nuclear reactions inside the stars.
 - burning of material inside the stars.
 - burning on the surfaces of the stars.

Explain the reasoning behind the choice you made.

9. The range of temperatures for average stars is
- 300 – 3,000 K
 - 300 – 30,000 K
 - 3,000 – 30,000 K
 - 30,000 – 300,000 K
 - 300,000 – 3,000,000 K

Explain the reasoning behind the choice you made.

10. If a red star and a blue star both have the same size (diameter) and both are the same distance from Earth, which one looks brighter in the sky?
- the red star
 - the blue star
 - same, because they are the same distance from Earth
 - same, because they are the same distance from Earth and the same size (diameter)
 - same, because they are the same distance from Earth, size (diameter), and temperature

Explain the reasoning behind the choice you made.

11. Which of the following is correct about the nature of planets and stars?
- Planets orbit around the Sun. Stars don't move.
 - Planets orbit around the Sun but stars move through space.
 - Planets and stars both orbit the Sun.

Explain the reasoning behind the choice you made.

12. Star A has a lifetime of 50 million years, while star B has a lifetime of only 10 million years. What can you say about the masses of these stars?
- Star A has the greatest mass.
 - Star B has the greatest mass.
 - Stars A and B have approximately the same mass.
 - There is not enough information given to answer this question.

Explain the reasoning behind the choice you made.

13. Which of the factors below does NOT influence how bright a star appears to us on Earth?
- shape
 - energy output
 - size (diameter)
 - temperature
 - distance

Explain the reasoning behind the choice you made.

14. Stars begin life as
- a piece off of another star.
 - a cloud of gas and dust.
 - a very large, hot planet.
 - a matter in Earth's atmosphere.
 - an asteroid.

Explain the reasoning behind the choice you made.

15. The hottest stars are what color?
- red
 - white
 - blue
 - none of these, because all stars are the same temperature
 - none of these, because all stars are the same color

Explain the reasoning behind the choice you made.

16. Stars are made mostly of which element when they first form?

- a. helium
- b. hydrogen
- c. carbon
- d. oxygen
- e. silicon

Explain the reasoning behind the choice you made.

17. The Sun is...

- a. a large planet
- b. a hot planet
- c. a small planet
- d. an old planet
- e. not a planet

Explain the reasoning behind the choice you made.

18. Where does the Sun's energy come from?

- a. the combining of elements into new elements
- b. radioactivity
- c. the glow from molten rocks
- d. heat left over from the Big Bang
- e. heat left over from the Sun's formation

Explain the reasoning behind the choice you made.

19. In which part of the Sun does nuclear fusion take place?

- a. photosphere
- b. corona
- c. core
- d. radiative layer
- e. nucleosphere

Explain the reasoning behind the choice you made.

20. Star A has a mass of 2 solar masses and star B has a mass of 4 solar masses. How will the fusion rate of star A compare to the fusion rate of star B?
- Star A's fusion rate will be more than two times slower than that of star B.
 - Star A's fusion rate will be two times slower than that of star B.
 - Star A's fusion rate will be the same as that of star B.
 - Star A's fusion rate will be two times faster than that of star B.
 - Star A's fusion rate will be more than two times faster than that of star B.

Explain the reasoning behind the choice you made.

21. Which of the following is correct about the nature of planets and stars?
- A planet makes its own light, but a star reflects sunlight.
 - A planet reflects sunlight, but a star makes its own light.
 - Both planets and stars make their own light.
 - Both planets and stars reflect sunlight.

Explain the reasoning behind the choice you made.

22. Molecular clouds are
- clouds of simple molecules expelled by dying stars.
 - clouds that contain many complex molecules.
 - cool clouds of gas and dust.
 - hot, active clouds of molecular gas

Explain the reasoning behind the choice you made.

23. Arrange the following stars by surface temperature from hottest to coldest: white stars, blue stars, and red stars.
- Hottest → Coldest
- red > white > blue
 - red > blue > white
 - white > red > blue
 - blue > white > red
 - blue > red > white

Explain the reasoning behind the choice you made.

24. Star A has a mass of 5 solar masses and Star B has a mass of 10 solar masses. How will the total lifetime of Star A compare to the total lifetime of Star B?
- a. Star A's total lifetime will be less than half as long as that of Star B.
 - b. Star A's total lifetime will be half as long as that of Star B.
 - c. Star A's total lifetime will be the same as that of Star B.
 - d. Star A's total lifetime will be twice as long as that of Star B.
 - e. Star A's total lifetime will be more than twice as long as that of Star B.

Explain the reasoning behind the choice you made.

25. The force that dominates the collapse of the gas and dust in a region that may eventually form a star is
- a. Static electricity.
 - b. gravity.
 - c. magnetism.
 - d. friction.
 - e. nuclear fusion.

Explain the reasoning behind the choice you made.

26. The property of stars that varies least is
- a. lifetime
 - b. mass
 - c. size (diameter)
 - d. temperature
 - e. energy output (brightness)

Explain the reasoning behind the choice you made.

27. Compared to most stars, the Sun is
- a. very large.
 - b. average size.
 - c. very small.
 - d. not a star.

Explain the reasoning behind the choice you made.

28. Stars A and B appear equally bright from Earth. However, star A actually gives off more light than star B. Which of the following is true about star A?
- It is the same distance from Earth as is star B.
 - It is farther away from Earth than is star B.
 - It is closer to Earth than is star B.
 - It has a smaller diameter than star B.
 - It is the same diameter as star B.

Explain the reasoning behind the choice you made.

29. How does the Sun produce the energy that heats our planet?
- The gases inside the Sun are burning and producing large amounts of energy.
 - Hydrogen is combined into helium, giving off large amounts of energy.
 - Gas inside the Sun heats up when compressed, giving off large amounts of energy.
 - Heat trapped by magnetic fields in the Sun is released as energy.
 - The core of the Sun has radioactive atoms that give off energy as they decay.

Explain the reasoning behind the choice you made.

30. Which of the following causes a star's interior temperature to increase during its formation?
- Nuclear fusion forces gravitational collapse, which generates a lot of heat.
 - Heat is generated when the star's gravity contracts.
 - Gravitational collapse involves the generation of heat from chemical reactions.
 - During collapse, gravitational potential energy is converted to heat.

Explain the reasoning behind the choice you made.

31. Would you be willing to participate in a short interview to discuss your responses to this survey? NOTE: Indicating "yes" to this does not guarantee you will be selected to be interviewed, and if selected, you will still have the opportunity to refuse the interview.
- Yes
 - No

32. What is your gender?

- a. Female
- b. Male

33. Have you had an astronomy course? (If you are taking this survey in an astronomy course, do NOT count it in your response.)

- a. Yes
- b. No

Star Formation Concept Inventory Version 1c

Version 1c was divided into six different forms. Each form had questions #31-33; forms had five additional questions each, in order (e.g., Form 1c-1 had questions #1-5). Spacing has been reduced for inclusion here.

1. What is a star?
2. Compared to the Sun, the greatest energy output (brightness) a star will ever have is how many times greater or smaller?
3. In an average star, how is gravitational collapse balanced?
4. Which fundamental property determines all characteristics and future events of a star's life?
5. How is the lifetime of a star related to its mass?
6. What is the name given to a star as it is initially forming?
7. What will happen to the Sun in the future?
8. The light from stars that we see on Earth results from what?
9. What is the range of temperatures average stars can have?
10. If a red star and a blue star both have the same size (diameter) and both are the same distance from Earth, which one looks brighter in the sky? Why?
11. Compare the motions of planets relative to the Sun to the motions of stars relative to the Sun.

12. Star A has a lifetime of 50 million years, while star B has a lifetime of only 10 million years. Which star has the greater mass? Why?
13. What factors or properties influence how bright a star appears to us on Earth?
14. What kinds of objects do stars come from?
15. The hottest stars are what color? Why?
16. Stars are made mostly of which elements when they first form? Why?
17. How does the Sun compare to a planet?
18. Where does the Sun's energy come from?
19. In which part of the Sun does nuclear fusion take place? Why?
20. Star A has a mass of 2 solar masses and star B has a mass of 4 solar masses. How will the fusion rate of star A compare to the fusion rate of star B? Why?
21. Compare how we see light from stars to how we see light from planets.
22. What are molecular clouds?
23. Arrange the following stars by surface temperature from hottest to coldest: white stars, blue stars, and red stars. Why did you choose the order you did?
24. Star A has a mass of 5 solar masses and Star B has a mass of 10 solar masses. How will the total lifetime of Star A compare to the total lifetime of Star B? Why?

25. What is the force that dominates the collapse of the gas and dust in a region that may eventually form a star?
26. What property of stars has the smallest range of values over which it can vary? What is this range?
27. How does the Sun's size compare to the sizes of most stars?
28. Stars A and B appear equally bright from Earth. However, star A actually gives off more light than star B. What is the relationship between the sizes of stars A and B?
29. How does the Sun produce the energy that heats our planet?
30. What causes a star's interior temperature to increase during its formation?
31. Would you be willing to participate in a short interview to discuss your responses to this survey? NOTE: Indicating "yes" to this does not guarantee you will be selected to be interviewed, and if selected, you will still have the opportunity to refuse the interview.
 - a. Yes
 - b. No
32. What is your gender?
 - a. Female
 - b. Male
33. Have you had an astronomy course? (If you are taking this survey in an astronomy course, do NOT count it in your response.)
 - c. Yes
 - d. No

APPENDIX H

STAR FORMATION CONCEPT INVENTORY, VERSION 2 (2 FORMATS)

Star Formation Concept Inventory
Version 2a

Version 2a was divided into two different forms. Each form had questions #31-33 plus 15 of the 30 questions.

1. What is a star?
 - a. a ball of gas that reflects light
 - b. a point of light in Earth's atmosphere
 - c. a ball of burning gas that gives off light
 - d. a round hot body that gives off light

2. Which of the following causes a star's interior temperature to increase during its formation?
 - a. Nuclear fusion forces gravitational collapse, which generates a lot of heat.
 - b. Heat is generated when the star's gravity contracts.
 - c. Gravitational collapse involves the generation of heat from chemical reactions.
 - d. During collapse, gravitational potential energy is converted to heat.

3. The force that dominates the collapse of the gas and dust in a region that may eventually form a star is
 - a. static electricity.
 - b. gravity.
 - c. magnetism.
 - d. pressure.
 - e. nuclear fusion.

4. Stars A and B appear equally bright from Earth. However, star A actually gives off more light than star B. Which of the following is true about star A?
 - a. It is the same distance from Earth as star B.
 - b. It is farther away from Earth than star B.
 - c. It is closer to Earth than star B.

5. Stars are made mostly of which types of atoms when they first form?
 - a. oxygen
 - b. nitrogen
 - c. carbon
 - d. helium
 - e. hydrogen

6. How does the surface temperature of other stars compare to the surface temperature of the Sun?
 - a. Nearly all other stars have lower surface temperatures than the Sun.
 - b. Nearly all other stars have higher surface temperatures than the Sun.
 - c. Some stars have lower and some have higher surface temperatures than the Sun.
 - d. All other stars have about the same surface temperature as the Sun.

7. Star A has a mass of 2 solar masses and star B has a mass of 4 solar masses. How will star A use its fuel compared to star B?
 - a. Star A will use up its fuel more than two times slower than star B.
 - b. Star A will use up its fuel two times slower than star B.
 - c. Star A will use up its fuel in the same amount of time as star B.
 - d. Star A will use up its fuel two times faster than star B.
 - e. Star A will use up its fuel more than two times faster than star B.

8. The hottest stars are what color?
 - a. red
 - b. white
 - c. blue
 - d. none of these, because all stars are the same surface temperature
 - e. none of these, because all stars are the same color

9. The Sun is...
 - a. a large planet.
 - b. a hot planet.
 - c. a small planet.
 - d. an old planet.
 - e. not a planet.

10. Why don't average stars collapse in on themselves under gravity's influence?
 - a. Material churning in and out of the star's core balances gravity.
 - b. The internal structure of the star keeps it from collapsing in on itself.
 - c. Gravity from planets orbiting the star pulls outward on the star.
 - d. The outward force from particles ejected during fusion will balance gravity.
 - e. Pressure caused by energy from during fusion pushes outward to balance gravity.

11. The property of stars that varies least is
 - a. lifetime.
 - b. mass.
 - c. size (diameter).
 - d. surface temperature.
 - e. energy output (brightness).

12. Star A has a total lifetime of 50 million years, while star B has a total lifetime of only 10 million years. What can you say about the masses of these stars?
 - a. Star A has the greater mass.
 - b. Star B has the greater mass.
 - c. Stars A and B have approximately the same mass.
 - d. There is not enough information given to answer this question.

13. What is the name given to a star as it is initially forming?
 - a. protostar
 - b. nebula
 - c. supernova
 - d. star cluster
 - e. white dwarf

14. Where does the Sun's energy come from?
 - a. the combining of atoms into new types of atoms
 - b. radioactivity
 - c. burning of gases
 - d. chemical reactions
 - e. heat left over from the Sun's formation

15. Stars begin life as
- a piece off of a star or planet.
 - a very large, hot planet.
 - matter in Earth's atmosphere.
 - a black hole.
 - a cloud of gas and dust.
16. A nebula is a
- cloud of simple atoms expelled by a dying star.
 - cloud that contains many gases and complex molecules.
 - cool cloud of gas and dust.
 - hot, active cloud of gas.
17. How does the energy output (brightness) of other stars compare to the energy output (brightness) of the Sun?
- Nearly all other stars give off less energy than the Sun.
 - Nearly all other stars give off more energy than the Sun.
 - Some stars give off more energy and some give off less energy than the Sun.
 - All other stars give off the same amount of energy as the Sun.
18. If a red star and a blue star both have the same size (diameter) and both are the same distance from Earth, which one looks brighter in the sky?
- the red star, because it is easier to see against the nighttime sky
 - the blue star, because it is hotter and therefore brighter
 - same, because they are the same distance from Earth
 - same, because they are the same distance from Earth and the same size (diameter)
 - same, because they are the same distance from Earth, size (diameter), and surface temperature
19. How is the lifetime of a star related to its mass?
- More massive stars live considerably longer lives than less massive stars.
 - More massive stars live considerably shorter lives than less massive stars.
 - More massive stars live slightly shorter lives than less massive stars.
 - More massive stars live slightly longer lives than less massive stars.
 - All stars have the same lifetimes regardless of mass.

20. In the future the Sun will
- use up all its fuel and will eventually stop shining.
 - explode as it burns out of control.
 - expand and grow forever.
 - continue to shine because it has a renewable supply of fuel.
21. The light from stars that we see on Earth results from
- reflection of sunlight.
 - chemical reactions inside the stars.
 - nuclear reactions inside the stars.
 - burning of material inside the stars.
 - burning on the surfaces of the stars.
22. Arrange the following stars by surface temperature from hottest to coldest: white stars, blue stars, and red stars.
- Hottest $\rightarrow$ Coldest
- white > blue > red
 - white > red > blue
 - red > blue > white
 - blue > white > red
 - blue > red > white
23. Stars are _____ planets.
- nearly identical to
 - older, hotter, and give off more energy than
 - smaller, hotter, and give off less energy than
 - larger, hotter, and give off more energy than
 - smaller, older, and give off less energy than
24. In which part of the Sun does nuclear fusion take place?
- radiative layer
 - nucleosphere
 - core
 - throughout the Sun
 - on the surface

25. How does the Sun produce the energy that heats our planet?
- The gases inside the Sun are burning and producing large amounts of energy.
 - Hydrogen is combined into helium, giving off large amounts of energy.
 - Gas inside the Sun heats up when compressed, giving off large amounts of energy.
 - Heat trapped by magnetic fields in the Sun is released as energy.
 - The core of the Sun has radioactive atoms that give off energy as they decay.
26. Star A has a mass of 5 solar masses and star B has a mass of 10 solar masses. How will the total lifetime of Star A compare to the total lifetime of star B?
- Star A's total lifetime will be less than half as long as that of star B.
 - Star A's total lifetime will be half as long as that of star B.
 - Star A's total lifetime will be the same as that of star B.
 - Star A's total lifetime will be twice as long as that of star B.
 - Star A's total lifetime will be more than twice as long as that of star B.
27. Which fundamental property determines all characteristics and future events of a star's life?
- surface temperature
 - size (diameter)
 - color
 - composition (type of atoms)
 - mass
28. Which of the factors below does NOT influence how bright a star appears to us on Earth?
- composition (type of atoms)
 - energy output (brightness)
 - size (diameter)
 - surface temperature
 - distance
29. How does the size (diameter) of other stars compare to the size (diameter) of the Sun?
- Nearly all other stars are smaller (in diameter) than the Sun.
 - Nearly all other stars are bigger (in diameter) than the Sun.
 - Some stars are smaller and some are bigger (in diameter) than the Sun.
 - All other stars are about the same size (diameter) as the Sun.

30. Which of the following is correct about the nature of planets and stars?
- a. A planet makes its own light, but a star reflects sunlight.
 - b. A planet reflects sunlight, but a star makes its own light.
 - c. Both planets and stars make their own light.
 - d. Both planets and stars reflect sunlight.
31. Would you be willing to participate in a short interview to discuss your responses to this survey? NOTE: Indicating “yes” to this does not guarantee you will be selected to be interviewed, and if selected, you will still have the opportunity to refuse the interview. If “yes,” please be sure your name is on the front of the survey.
- a. Yes
 - b. No
32. What is your gender?
- a. Female
 - b. Male
33. Have you had an astronomy course? (If you are taking this survey in an astronomy course, do NOT count it in your response.)
- a. Yes
 - b. No

Star Formation Concept Inventory Version 2b

Version 2b was divided into four different forms. Each form had questions #31-33; remaining questions were divided among the different forms (Version 2b-1, #1-8; Version 2b-2, #9-15; Version 2b-3, #16-22; and Version 2b-4, #23-30). Spacing has been reduced for inclusion here.

1. What is a star?
 - a. a ball of gas that reflects light
 - b. a point of light in Earth's atmosphere
 - c. a ball of burning gas that gives off light
 - d. a round hot body that gives off light

Explain the reasoning behind the choice you made.

2. Which of the following causes a star's interior temperature to increase during its formation?
 - a. Nuclear fusion forces gravitational collapse, which generates a lot of heat.
 - b. Heat is generated when the star's gravity contracts.
 - c. Gravitational collapse involves the generation of heat from chemical reactions.
 - d. During collapse, gravitational potential energy is converted to heat.

Explain the reasoning behind the choice you made.

3. The force that dominates the collapse of the gas and dust in a region that may eventually form a star is
 - a. static electricity.
 - b. gravity.
 - c. magnetism.
 - d. pressure.
 - e. nuclear fusion.

Explain the reasoning behind the choice you made.

4. Stars A and B appear equally bright from Earth. However, star A actually gives off more light than star B. Which of the following is true about star A?
- It is the same distance from Earth as star B.
 - It is farther away from Earth than star B.
 - It is closer to Earth than star B.

Explain the reasoning behind the choice you made.

5. Stars are made mostly of which types of atoms when they first form?
- oxygen
 - nitrogen
 - carbon
 - helium
 - hydrogen

Explain the reasoning behind the choice you made.

6. How does the surface temperature of other stars compare to the surface temperature of the Sun?
- Nearly all other stars have lower surface temperatures than the Sun.
 - Nearly all other stars have higher surface temperatures than the Sun.
 - Some stars have lower and some have higher surface temperatures than the Sun.
 - All other stars have about the same surface temperature as the Sun.

Explain the reasoning behind the choice you made.

7. Star A has a mass of 2 solar masses and star B has a mass of 4 solar masses. How will star A use its fuel compared to star B?
- Star A will use up its fuel more than two times slower than star B.
 - Star A will use up its fuel two times slower than star B.
 - Star A will use up its fuel in the same amount of time as star B.
 - Star A will use up its fuel two times faster than star B.
 - Star A will use up its fuel more than two times faster than star B.

Explain the reasoning behind the choice you made.

8. The hottest stars are what color?
- a. red
 - b. white
 - c. blue
 - d. none of these, because all stars are the same surface temperature
 - e. none of these, because all stars are the same color

Explain the reasoning behind the choice you made.

9. The Sun is...
- a. a large planet.
 - b. a hot planet.
 - c. a small planet.
 - d. an old planet.
 - e. not a planet.

Explain the reasoning behind the choice you made.

10. Why don't average stars collapse in on themselves under gravity's influence?
- a. Material churning in and out of the star's core balances gravity.
 - b. The internal structure of the star keeps it from collapsing in on itself.
 - c. Gravity from planets orbiting the star pulls outward on the star.
 - d. The outward force from particles ejected during fusion will balance gravity.
 - e. Pressure caused by energy from during fusion pushes outward to balance gravity.

Explain the reasoning behind the choice you made.

11. The property of stars that varies least is
- a. lifetime.
 - b. mass.
 - c. size (diameter).
 - d. surface temperature.
 - e. energy output (brightness).

Explain the reasoning behind the choice you made.

12. Star A has a total lifetime of 50 million years, while star B has a total lifetime of only 10 million years. What can you say about the masses of these stars?
- Star A has the greater mass.
 - Star B has the greater mass.
 - Stars A and B have approximately the same mass.
 - There is not enough information given to answer this question.

Explain the reasoning behind the choice you made.

13. What is the name given to a star as it is initially forming?
- protostar
 - nebula
 - supernova
 - star cluster
 - white dwarf

Explain the reasoning behind the choice you made.

14. Where does the Sun's energy come from?
- the combining of atoms into new types of atoms
 - radioactivity
 - burning of gases
 - chemical reactions
 - heat left over from the Sun's formation

Explain the reasoning behind the choice you made.

15. Stars begin life as
- a piece off of a star or planet.
 - a very large, hot planet.
 - matter in Earth's atmosphere.
 - a black hole.
 - a cloud of gas and dust.

Explain the reasoning behind the choice you made.

16. A nebula is a

- a. cloud of simple atoms expelled by a dying star.
- b. cloud that contains many gases and complex molecules.
- c. cool cloud of gas and dust.
- d. hot, active cloud of gas.

Explain the reasoning behind the choice you made.

17. How does the energy output (brightness) of other stars compare to the energy output (brightness) of the Sun?

- a. Nearly all other stars give off less energy than the Sun.
- b. Nearly all other stars give off more energy than the Sun.
- c. Some stars give off more energy and some give off less energy than the Sun.
- d. All other stars give off the same amount of energy as the Sun.

Explain the reasoning behind the choice you made.

18. If a red star and a blue star both have the same size (diameter) and both are the same distance from Earth, which one looks brighter in the sky?

- a. the red star, because it is easier to see against the nighttime sky
- b. the blue star, because it is hotter and therefore brighter
- c. same, because they are the same distance from Earth
- d. same, because they are the same distance from Earth and the same size (diameter)
- e. same, because they are the same distance from Earth, size (diameter), and surface temperature

Explain the reasoning behind the choice you made.

19. How is the lifetime of a star related to its mass?

- a. More massive stars live considerably longer lives than less massive stars.
- b. More massive stars live considerably shorter lives than less massive stars.
- c. More massive stars live slightly shorter lives than less massive stars.
- d. More massive stars live slightly longer lives than less massive stars.
- e. All stars have the same lifetimes regardless of mass.

Explain the reasoning behind the choice you made.

20. In the future the Sun will
- use up all its fuel and will eventually stop shining.
 - explode as it burns out of control.
 - expand and grow forever.
 - continue to shine because it has a renewable supply of fuel.

Explain the reasoning behind the choice you made.

21. The light from stars that we see on Earth results from
- reflection of sunlight.
 - chemical reactions inside the stars.
 - nuclear reactions inside the stars.
 - burning of material inside the stars.
 - burning on the surfaces of the stars.

Explain the reasoning behind the choice you made.

22. Arrange the following stars by surface temperature from hottest to coldest: white stars, blue stars, and red stars.

Hottest → Coldest

- white > blue > red
- white > red > blue
- red > blue > white
- blue > white > red
- blue > red > white

Explain the reasoning behind the choice you made.

23. Stars are _____ planets.
- nearly identical to
 - older, hotter, and give off more energy than
 - smaller, hotter, and give off less energy than
 - larger, hotter, and give off more energy than
 - smaller, older, and give off less energy than

Explain the reasoning behind the choice you made.

24. In which part of the Sun does nuclear fusion take place?

- a. radiative layer
- b. nucleosphere
- c. core
- d. throughout the Sun
- e. on the surface

Explain the reasoning behind the choice you made.

25. How does the Sun produce the energy that heats our planet?

- a. The gases inside the Sun are burning and producing large amounts of energy.
- b. Hydrogen is combined into helium, giving off large amounts of energy.
- c. Gas inside the Sun heats up when compressed, giving off large amounts of energy.
- d. Heat trapped by magnetic fields in the Sun is released as energy.
- e. The core of the Sun has radioactive atoms that give off energy as they decay.

Explain the reasoning behind the choice you made.

26. Star A has a mass of 5 solar masses and star B has a mass of 10 solar masses. How will the total lifetime of Star A compare to the total lifetime of star B?

- a. Star A's total lifetime will be less than half as long as that of star B.
- b. Star A's total lifetime will be half as long as that of star B.
- c. Star A's total lifetime will be the same as that of star B.
- d. Star A's total lifetime will be twice as long as that of star B.
- e. Star A's total lifetime will be more than twice as long as that of star B.

Explain the reasoning behind the choice you made.

27. Which fundamental property determines all characteristics and future events of a star's life?

- a. surface temperature
- b. size (diameter)
- c. color
- d. composition (type of atoms)
- e. mass

Explain the reasoning behind the choice you made.

28. Which of the factors below does NOT influence how bright a star appears to us on Earth?
- a. composition (type of atoms)
 - b. energy output (brightness)
 - c. size (diameter)
 - d. surface temperature
 - e. distance

Explain the reasoning behind the choice you made.

29. How does the size (diameter) of other stars compare to the size (diameter) of the Sun?
- a. Nearly all other stars are smaller (in diameter) than the Sun.
 - b. Nearly all other stars are bigger (in diameter) than the Sun.
 - c. Some stars are smaller and some are bigger (in diameter) than the Sun.
 - d. All other stars are about the same size (diameter) as the Sun.

Explain the reasoning behind the choice you made.

30. Which of the following is correct about the nature of planets and stars?
- a. A planet makes its own light, but a star reflects sunlight.
 - b. A planet reflects sunlight, but a star makes its own light.
 - c. Both planets and stars make their own light.
 - d. Both planets and stars reflect sunlight.

Explain the reasoning behind the choice you made.

31. Would you be willing to participate in a short interview to discuss your responses to this survey? NOTE: Indicating “yes” to this does not guarantee you will be selected to be interviewed, and if selected, you will still have the opportunity to refuse the interview. If “yes,” please be sure your name is on the front of the survey.
- a. Yes
 - b. No

32. What is your gender?

- a. Female
- b. Male

33. Have you had an astronomy course? (If you are taking this survey in an astronomy course, do NOT count it in your response.)

- a. Yes
- b. No

APPENDIX I

EXPERT REVIEW DOCUMENTS

The following documents represent the Expert Review process. First is the recruitment letter, sent through Astrolrner, a Yahoo! Groups, moderated listserve for the astronomy education community. Next is the instructions sent to the volunteer reviewers, followed by the SPCI 2.5. The reviewers' comments are compiled into a large table starting after the inventory. Finally, included is a copy of a letter sent to all reviewers after responses were received.

Recruitment Letter to Astrolrner Listserve

July 12, 2005

Dear Astrolrner Readers,

As part of an ongoing study into undergraduate students' understanding of the properties of stars, I am developing a concept inventory that will eventually be used in the classroom. The concept inventory currently has about 25 multiple-choice questions (plus a few "demographic" questions to help me describe my volunteer reviewers). I am looking for instructors to take and comment on the latest version as a way of establishing the content validity of the instrument.

If you are interested in participating in this project, please reply to me at jbailey@as.arizona.edu (PLEASE DO NOT REPLY TO THE LISTSERVE). I will email instructions, the concept inventory, and an answer/comment sheet to you within two days. Please let me know if you need documents in .rtf format rather than .doc. I ask for your responses as soon as possible, but no later than July 29.

Thank you in advance for your time and participation!

Janelle M. Bailey
Ph.D. Candidate

Star Properties Concept Inventory
Version 2.5

Expert Review for Content Validity

INSTRUCTIONS TO REVIEWERS

1. Please complete the answer sheet that accompanies these instructions (next page), indicating the best response to each question.
2. Please provide any specific comments about the questions in the next column. For example, you may have suggestions about the wording of a question or its choices, alternative questions you feel could help this study, etc.
3. Please SAVE your responses (same or new name, doesn't matter).
4. Please return the file with your answers and comments to me at jbailey@as.arizona.edu prior to 5:00pm Friday, July 29, 2005.

Thank you very much for your participation. Please do not hesitate to contact me if you have any questions!

Janelle Bailey
jbailey@as.arizona.edu
520-626-9480 or 520-360-7322

Star Properties Concept Inventory
Version 2.5

1. When they first form, stars are made mostly of which one type of atom?
 - a. oxygen
 - b. nitrogen
 - c. carbon
 - d. helium
 - e. hydrogen

2. Which of the following causes a star's interior temperature to increase during its formation?
 - a. Nuclear fusion causes gravitational collapse, which generates heat.
 - b. Heat is generated when the star's gravity contracts.
 - c. Gravitational collapse involves the generation of heat from chemical reactions.
 - d. During collapse, gravitational potential energy is converted to heat.

3. How does the Sun's surface temperature compare to that of other stars?
 - a. The Sun has the highest surface temperature of any star.
 - b. The Sun has the lowest surface temperature of any star.
 - c. The Sun has neither the lowest nor the highest surface temperature of any star.
 - d. The Sun has about the same surface temperature as all other stars.

4. In which part of a star is its energy produced?
 - a. radiative layer
 - b. nucleosphere
 - c. core
 - d. throughout the star
 - e. on the surface

5. Star A has 2 times the mass of the Sun, while star B has 4 times the mass of the Sun. How will star A use up its fuel compared to star B?
 - a. Star A will use up its fuel more than two times slower than star B.
 - b. Star A will use up its fuel two times slower than star B.
 - c. Star A will use up its fuel in the same amount of time as star B.
 - d. Star A will use up its fuel two times faster than star B.
 - e. Star A will use up its fuel more than two times faster than star B.

6. The force that dominates the collapse of the gas and dust in a region that may eventually form a star is
 - a. static electricity.
 - b. gravity.
 - c. magnetism.
 - d. pressure.
 - e. nuclear fusion.
7. The hottest stars are what color?
 - a. red
 - b. white
 - c. blue
 - d. none of these, because all stars have the same surface temperature
 - e. none of these, because all stars are the same color
8. Why don't most stars collapse in on themselves under gravity's influence?
 - a. Material churning in and out of the star's core balances gravity.
 - b. The internal structure of the star keeps it from collapsing in on itself.
 - c. Gravity from planets orbiting the star pulls outward on the star's material.
 - d. The outward force from particles ejected during fusion balances gravity.
 - e. Pressure caused by energy from fusion pushes outward to balance gravity.
9. Which object has the highest surface temperature?
 - a. a typical red giant
 - b. a typical white dwarf
 - c. the Sun
 - d. These objects could have the same temperature.
10. Star A has a total lifetime of 50 million years, while star B has a total lifetime of only 10 million years. What can you say about the masses of these stars?
 - a. Star A has the greater mass.
 - b. Star B has the greater mass.
 - c. Stars A and B have about the same mass.
 - d. There is not enough information given to answer this question.
11. What is the name given to a star as it is initially forming?
 - a. protostar
 - b. nebula
 - c. supernova
 - d. star cluster
 - e. white dwarf

12. Where does the Sun's energy come from?
- a. the combining of atoms into new types of atoms
 - b. radioactivity
 - c. burning of gases
 - d. chemical reactions
 - e. breaking apart of atoms into new types of atoms
13. Which object is most massive: a red giant, a white dwarf, or the Sun?
- a. A red giant is always the most massive.
 - b. A white dwarf is always the most massive.
 - c. The Sun is the most massive.
 - d. These objects could have the same mass.
14. Stars begin life as
- a. a piece off of a star or planet.
 - b. a white dwarf.
 - c. matter in Earth's atmosphere.
 - d. a black hole.
 - e. a cloud of gas and dust.
15. The Sun's brightness (energy output) is...
- a. near the high end of star brightnesses.
 - b. near the low end of star brightnesses.
 - c. near the middle of star brightnesses.
 - d. about the same as the brightnesses of all other stars.
16. What is a star?
- a. a ball of gas that reflects light from another energy source
 - b. a bright point of light visible in Earth's atmosphere
 - c. a hot ball of gas that produces energy by burning gases
 - d. a hot ball of gas that produces energy by combining light atoms into heavier atoms
 - e. a hot ball of gas that produces energy by breaking apart heavy atoms into lighter atoms
17. If a red star and a blue star have the same size (diameter) and are at the same distance from Earth, which one will look brighter?
- a. the red star
 - b. the blue star
 - c. Both stars will look the same.
 - d. There is not enough information given to answer this question.

18. How is the lifetime of a star related to its mass?
- More massive stars live considerably longer lives than less massive stars.
 - More massive stars live considerably shorter lives than less massive stars.
 - More massive stars live slightly shorter lives than less massive stars.
 - More massive stars live slightly longer lives than less massive stars.
 - All stars have the same lifetimes regardless of mass.
19. Which object has the greatest energy output (brightness): a red giant, a white dwarf, or the Sun?
- A red giant always has the greatest energy output (brightness).
 - A white dwarf always has the greatest energy output (brightness).
 - The Sun has the greatest energy output (brightness).
 - These objects could have the same energy output (brightness).
20. The light from stars that we see on Earth results from
- reflection of sunlight.
 - chemical reactions inside the stars.
 - nuclear reactions inside the stars.
 - burning of material inside the stars.
 - burning on the surfaces of the stars.
21. How would you rank the surface temperatures of red, white, and blue stars?
	<i>Hottest</i>		→		<i>Coldest</i>
a.	white	>		blue	> red
b.	white	>		red	> blue
c.	red	>		blue	> white
d.	blue	>		white	> red
e.	blue	>		red	> white
22. How does the Sun produce the energy that heats our planet?
- The gases inside the Sun are burning and producing energy.
 - Light elements are combined into heavier elements, giving off energy.
 - Gas inside the Sun heats up when compressed, giving off energy.
 - Heavy elements are broken apart into lighter elements, giving off energy.
 - The core of the Sun has radioactive atoms that give off energy as they decay.
23. Which of the following would give off the most energy?
- a small red star
 - a large red star
 - a small blue star
 - a large blue star

24. Star A has 5 times the mass of the Sun, while star B has 15 times the mass of the Sun. How will the total lifetime of Star A compare to the total lifetime of star B?
- a. Star A's total lifetime will be less than one-third as long as that of star B.
 - b. Star A's total lifetime will be one-third as long as that of star B.
 - c. Star A's total lifetime will be the same as that of star B.
 - d. Star A's total lifetime will be three times as long as that of star B.
 - e. Star A's total lifetime will be more than three times as long as that of star B.
25. Which of the following determines all characteristics and future events of a star's life?
- a. surface temperature
 - b. size (diameter)
 - c. color
 - d. composition (type of atoms)
 - e. mass
26. The Sun's size (diameter) is...
- a. near the high end of star sizes (diameters).
 - b. near the low end of star sizes (diameters).
 - c. near the middle of star sizes (diameters).
 - d. about the same as the sizes (diameters) of all other stars.

The following questions are asked so that I can accurately describe the volunteer reviewers. Please write your answer on the answer sheet.

27. What is your highest degree received?
28. In what field/subject was this degree?
29. In what kind of institution (e.g., four-year university, community college, K-12 school, government agency, etc.) do you work?
30. Have you ever taught or do you currently teach astronomy? If so, at what level and for how long?

Compiled reviewers' comments. Numbers refer to the identification number that was randomly assigned to each reviewer.

Item #	Comment(s)
1	<p>3. I don't see the need for the word "one" in the phrasing. The instructions already indicate that only one answer should be chosen.</p> <p>5. OK</p> <p>8. This is a very good question, with impact on a lot of subjects besides stars.</p> <p>11. When stars are first formed, they are made mostly of which one of the following:</p> <p>12. Strike "one type of atom" replace with element.</p> <p>18. Just a personal note, when I ask a multiple choice question with such simple answers, I like to alphabetize them so the students don't try to second-guess my intentions in ordering the choices. I know, I'm odd that way.</p> <p>22. Could use "element" instead of atom, since stars form first from molecular clouds</p> <p>24. Iron might make another good distracter here. Students always remember that iron is important, but often don't remember why.</p> <p>25. Good basic question.</p>
2	<p>2. but b) needs only "star's gravity" changed to "star gravitationally" to be correct, so it needs to be replaced with a "wronger" phrase.</p> <p>4. B is a good distracter</p> <p>5. This question appears awkwardly worded to me.</p> <p>7. I notice the number of answers to each question varies between 4 or 5. I think the number of choices should be the same for all questions.</p> <p>8. Some of the distracters are bad science, but that may be your aim.</p> <p>10. Avoid use of "heat" as a noun; it is a process, not an object.</p> <p>11. Choice B is very similar to D and I almost picked it. The difference in the answers seems to be caused by a minor word ordering. I assume this test is designed to test for a complete misunderstanding. I don't think the question does that now. Suggested answers: A) Nuclear fusion (or, better yet, a layman's language version of that), B) Gravity, C) Chemical reactions (or "burning"?), D) Some other choice (perhaps none of the above?) I would NOT offer: atoms moving faster (i.e. increased kinetic energy, which IS an increase in temperature.)</p> <p>13. Perhaps put "during its formation" at <i>beginning</i> of sentence, in case a student is thinking of increase in temp during star's later evolution?</p> <p>15. Choice b may be a give-away since gravity is used as a noun and it sounds weird to my ears. I'm sure that many undergrads won't notice, but kids with something of a technical background will.</p> <p>16. b is a confusing answer because of the phrase "gravity contracts", do you mean gravity contracts the star, in which case it is too similar to d for a non-science student.</p> <p>17. Reword to stress student identification of energy source (unless the intent is to distinguish between "gravitational collapse," "gravity contracts," etc.). EXAMPLE: What causes a star's core temperature to increase during its formation? (a) Nuclear fusion. (b) Density increase? Nuclear fission? Changes in gravity? (c) Chemical reactions. (d) Gravitational potential energy.</p> <p>18. This is a question about star formation or gravity, not the properties of stars – is it appropriate for the objective of this concept inventory?</p> <p>20. For non-native English speakers, answers b and d will sound suspiciously alike. You may get the "wrong" answer for the wrong reason.</p> <p>21. I read "B" originally as "heat is generated when the star's gravity contracts <u>it</u>". This would be correct (as well as "D"). I consider this to be an ill phrased. This is testing a student's ability to read a question completely, not the concept.</p> <p>22. Distracter b is nonsense, but may confuse some non-native-English speakers into choosing it.</p> <p>23. B is incorrect for a very subtle reason. I wonder if even a student who understood the process would choose this because all the right words are there.</p> <p>25. I'd suggest changing wording to that answer, ...star's gravity contracts star's mass, generating heat</p> <p>26. For b) Gravity is a phenomenon, it cannot contract. Star can contract due to gravity but then b) is correct</p>

Item #	Comment(s)
3	<p>3. The options are very "closed". I would prefer a phrasing like "around the highest possible" and "around the lowest possible". Having the Sun BE the highest or lowest is so unlikely that the distracters become less attractive.</p> <p>4. D could be an answer. "about" – yes if you consider the full range of astronomical temperatures: $2.7K - 10^6$. D is one of the possibilities for a naïve and a very sophisticated person. I don't like D as a distracter.</p> <p>8. I like distracter d.</p> <p>10. "About the same" is somewhat vague</p> <p>11. The difference between C & D is too small – I would find another way to distinguish between those two answers – I just can't think of one right now. Some might say the Sun is "average" which would indicate D. However, number-wise, there are many more M, L, and T stars than all others, so the Sun is far above the median, I'm guessing. Hence choice C. As worded, C & D could both be correct.</p> <p>16. Is the point that the Sun is an "average" star?</p> <p>18. I wonder how many students would pick "D" thinking that it implies some sort of average. It is clearly an incorrect option, however.</p> <p>23. D could be understood to as the Sun is and average star, which is what I teach the students</p> <p>25. OK, but like question 1, is a "factoid" type of question.</p>
4	<p>2. add "when it is on the main sequence"</p> <p>4. At least for a main seq. star. You might change it to "a main sequence star" protostars "generate energy throughout its envelope due to grav. Pot. Energy. Some end phase stars have inert cores & fusing shells</p> <p>7. The assumption is you are taking about the main sequence stage, but you don't state that. In other stages, energy source could be from gravitational contraction or shell burning.</p> <p>11. I expect very few students would get this wrong, unless I did. I reiterate that "concept inventories" should not be vocabulary-centered, and this question is, when it uses terms like "nucleosphere" which I've never heard of.</p> <p>14. Is "nucleosphere" supposed to be a bogus distracter?</p> <p>16. Do you mean nuclear energy? Might be confusing</p> <p>17. Is it important to avoid technical terms such as "radiative layer" and "nucleosphere" in a concept inventory given as a pre-test? Perhaps a cross-sectional diagram can be shown instead (I = core, II = middle layers (radiation zone); III = outer layers (convection/photosphere), with the following choices: (a) I only. (b) II only. (c) III only. (d) I and II. (e) II and III. (f) I, II, and III.</p> <p>18. I don't like "nucleosphere" – it is a made-up word as opposed to a more legitimate distracter.</p> <p>19. Too technical for my students: I would offer choices more like of (a) the hot outer part that we see, (b) the burning part (c), outer atmosphere or corona, (d) only in the core, (e) throughout the hot star.</p> <p>22. May want to specify "during its main sequence lifetime" since shell burning can occur later on. Since energy is conserved, it is not really "produced" in a star, either, so perhaps use "mass converted to energy" or "energy released" instead. Also can rephrase the question as a statement: "The part of a star in which energy is released is its:"</p> <p>23. C is correct for most stars, but for late type stars there are many layers. Should "most of the energy" be used in the question</p> <p>24. What's a nucleosphere? It distracted me!</p> <p>25. Ambiguous, as there is energy transfer throughout, maybe reword question as "where does the major energy of the star originate?"</p> <p>26. Would you like to add main-sequence star (or most stars) to distinguish from shell fusion around the core?</p>

Item #	Comment(s)
5	<p>2. Why not just say "Star B is twice as massive as star A." Never try to be tricky in multiple choice questions. But anyway, this question is repetitive of, and inferior to, question 10.</p> <p>3. Using 2 and 4 creates an extra variable, the number 4, that is not used in the choices. I would prefer comparing the mass of a star directly to the Sun instead of to another star that has a different mass than the Sun.</p> <p>4. Question 24 is better worded. (1) I would word the question the other way: "how will star B use up its fuel." Wording it this way makes me stop and think carefully not to invert the answer. I'd like to keep the logic separate from content. (2) it is confusing to say "more" and "slower" my wife the English prof doesn't have a suggestion, though.</p> <p>6. The English here seems awkward: "use up its fuel more than two times slower". Perhaps using the word "rate" would help...</p> <p>7. Since your options are only time related, in the question sentence, why not say "How fast will star A . . ."</p> <p>9. The wording is confusing when the word more and slower are used in the same statement.</p> <p>10. Does this refer to total available fuel, or fuel consumption rate? I'm not sure of the relevance of throwing the sun in there, why not just go with a comparison of A to B? Language "times slower" is awkward.</p> <p>11. 2 times → twice. Two times slower → half as fast. I would use answers that start with "Star B will use ..." rather than star A. I teach that heavier stars burn faster. This tests that, but the question is worded "backwards." That's not necessarily a bad thing, but it could throw some people. This is a personal preference rather than a (hopefully constructive) criticism.</p> <p>12. You can strike the "How will star" And move directly to the choices</p> <p>13. Could be confusing: are you interested in determining their understanding of the relative <i>rates</i> at which fuel is being used, or the total <i>time</i> it takes before stars run out of fuel? "C" clearly indicates the latter, but I'm not sure about the others.</p> <p>14. Four questions (Nos. 5, 10, 18 & 24) all test the same concept</p> <p>16. Is the mathematical relationship for lifetime and mass important for the students to know?</p> <p>18. Why the mathematical implication? I, personally, limit the amount of math in the intro AST course. Wouldn't a "high-mass" vs "low-mass" star comparisons suffice to test the concept?</p> <p>19. Good question</p> <p>21. This is another question that I believe would be more of a test of a student's ability to parse English than a student's knowledge of the concept. How often do you say "will use up its fuel more than X times slower"?</p> <p>22. Why mention a comparison to our own Sun in the first place? Also "more than two times slower" is problematic for non-native-English speakers. A better question would be: "Star Y has twice the mass of star Z....", which would make "e" correct. (Avoid using A and B as labels since they can be confused with answer choices A and B).</p> <p>25. Distracter about the Sun is not necessary for the point of the question, Could be stated as "Star A is one half the mass of Star B..."</p>
6	<p>2. Actually "friction" is a better choice, so I don't like this question.</p> <p>4. Though eventually D "pressure" comes in.</p> <p>8. I note that nuclear fusion isn't a force, though the heat generated by fusion can apply a force...</p> <p>11. Are the other choices common answers? This, again, seems too "easy." I use a similar question when asking what makes planets orbit. Nobody gets it wrong, making it a bad question (which I should abandon).</p> <p>18. You've listed two options that aren't "forces" – is that intentional? Or were you using the non-physical meaning of "force"?</p> <p>19. For my students, I would frame the question using the term "drives the collapse" rather than "dominates the collapse".</p> <p>21. The word "collapse" gives away the answer in my mind. But maybe not for the typical student (heck, I suspect many think magnetism holds the moon in orbit around the earth).</p> <p>24. Magnetism might not be the best distracter due to the Parker instability. Although you say "dominates", that magnetism can trigger star formation makes this a bad distracter. The same is true of pressure, in that pressure from an expanding supernova remnant can also trigger star formation.</p>

Item #	Comment(s)
7	<p>2. d and e are just filler choices. I'd pick other colors instead.</p> <p>5. I had trouble with this one. I wanted to say blue, but white was also hot. White is not really a color, of course, but a composite of colors. I would remove white and replace it with yellow.</p> <p>6. Poor choice of options. "Blue" and "white" are both accurate descriptions of the hottest stars, which appear a very pastel bluish-white to the eye. I would settle on two choices for color: red and blue, for "hot" and "cold", in all questions.</p> <p>7. I'm not comfortable with using white as the usual order I've encountered is red, blue, blue-white with the last being the hottest. How about rewording and saying "Compared to other stars, the hottest stars appear what?" redder, greener, bluer, etc.</p> <p>10. "all stars ..." in D and E does not exclude A, B, or C, so cannot be "none of these, because ...". If all stars had the same temperature, they could all be red, or white, or blue. How about a: hot stars are blue and cold stars are red, hot stars are red and cold stars are blue, all stars are the same color whatever their temperature, the color of stars is not related to temperature, all stars have the same color and temperature</p> <p>11. Good question. I may steal your answers. I think I give 5 colors or 4 plus "none of the above" when I use this same question.</p> <p>18. Fine question.</p> <p>19. This is a bit tricky because while most students can relate to something hot appearing red or possibly even white...seeing "blue" is outside their experience. For clarity perhaps you might reframe the question as "The very hottest stars appear to our eyes as mostly what color?"</p> <p>22. "c" because white dwarfs are the hottest stars, but some students will call this a trick question because they were thinking only about stars on the main sequence. Also, most stars at night from Earth appear white because of our poor color sense in the dark. So the question might be called subjective. You could say "On a color photograph..."</p> <p>24. White is probably not a very good distracter, since some instructors explain why UV peaking stars appear white.</p> <p>25. Great basic question</p> <p>26. Maybe reddish, bluish instead of red, blue?</p>

Item #	Comment(s)
8	<p>2. d gives one pause</p> <p>3. Physically, there is not a real difference between options "d" and "e". One could argue that photons are particles of light and pressure is just force per unit area.</p> <p>4. Though I could argue B if "internal structure" means the pressure, temp, state of the fluid/gas</p> <p>6. Option "b" can be interpreted as correct, if one accepts "pressure" are part of the internal structure of a star (and I might). Option "d" can also be interpreted as correct, since photons are particles. I would change options "b" and "d".</p> <p>7. One could argue that "b" is also correct in that "pressure generated from nuclear fusion" is part of the internal structure.</p> <p>8. Though b. is an arguable point—the internal structure is maintained by the heat generated by fusion.</p> <p>9. If the statement ended withto balance the force of gravity, it would parallel the definition of pressure which is force/area.</p> <p>10. Maybe specify that it is thermal pressure or gas pressure, as opposed to gravitational pressure (force/area), which acts inwards.</p> <p>11. I think E is the best choice, but I don't like it. Gas pressure or radiation pressure are better answers, which technically E allows. But you can have either gas or radiation pressure without fusion – that's why stars don't immediately collapse while forming. Gas pressure balances gravity short-term in star formation. Perhaps say "Pressure caused by collisions between upper and lower layers"? That's not great either, though. My question uses vocabulary (e.g. degeneracy pressure).</p> <p>14. I would suggest saying "nuclear fusion" in answer E.</p> <p>15. Choice b would be more convincing if it was written with more of a mechanism – maybe "The internal structure of the star holds the surface out..." Um, something like that, maybe.</p> <p>17. Reword (d) slightly to emphasize outwards nature of ejected particles: (d) The force from particles ejected outwards from fusion balances gravity.</p> <p>18. Wouldn't a practiced taker of MC tests go back and change the other questions dealing with gravity? I'm fine with that during a regular exam, but during a pre-test, you might be testing skill versus content knowledge here.</p> <p>21. What kind of pressure holds up the star? It is not gas pressure, its radiative pressure. This is hinted at in the wording, but frankly, I think most students don't know what pressure <u>is</u>. I usually say "radiation pushes the gas outward".</p> <p>22. Although one could argue that "b" is also correct in a vague sense. Perhaps replace "internal structure" with "solid structure" for this distracter.</p> <p>24. D is a very good distracter.</p> <p>25. B and D are viable answers, maybe reword</p>
9	<p>3. Nice in combination with question 7, although the difference in wording; a "star" (question 7) and "object" (stellar remnant, question 9) is too subtle for most students to notice I think.</p> <p>5. OK</p> <p>8. Good question!</p> <p>9. It is hard to know what a typical red giant and white dwarf would be – they both have a wide range of temperatures – just as soon not use the word typical.</p> <p>10. Try "Of the following objects, which has the highest surf temp: typical RG, typical WD, Sun." Otherwise, there are objects with higher surface temperature.</p> <p>11. Nice question!</p> <p>16. OK, could make it a "ranking" question</p> <p>18. In a pre-test situation, is this intended to test knowledge of the relation between color and temperature or the different stellar classifications? Not all students think the Sun is yellow, but rather there are some who say it's white.</p> <p>19. Maybe add e – There is not enough information given to answer this question</p> <p>22. One of questions 7 and 9 is redundant, i.e. I suspect that those answering 7 correctly will always answer 9 correctly (and similarly for wrong answers). Unless you are trying to test for something much more subtle than I can detect, of course!</p> <p>25. Good question</p> <p>26. Maybe to put "typical" in bold to emphasize it, otherwise some students may choose d.</p>

Item #	Comment(s)
10	<p>2. much better than question 5</p> <p>6. You must add the phrase “main-sequence” before “lifetime” in the question (both times) or, else this is an ambiguous question.</p> <p>10. Unless it is in some binary system, or is involved in a “collision” that disrupts the star significantly. Could be D, but that is quite deep.</p> <p>11. Another good question. I like it in conjunction with (and not next to) the fuel-burning question (#5)</p> <p>14. Four questions (Nos. 5, 10, 18 & 24) all test the same concept.</p> <p>16. OK (better than #5)</p> <p>18. I much prefer this question to question number five. Same concept being tested, while minimizing math anxiety.</p> <p>21. You could also ask how the masses of these stars compares to that of the Sun, both of the stars would be extremely massive compared to the Sun.</p> <p>22. “d” will be avoided even by guessers.</p> <p>25. Similar to prior question number 5</p> <p>26. Could you choose names for these stars to avoid confusion with A, B spectral types?</p>
11	<p>2. but who cares</p> <p>3. Option "a" is a strong distracter because it incorporates the word "star". It depends on what you mean by "initially forming" which of the options "a" or "b" is correct.</p> <p>5. There is some confusion in my mind regarding this question. Nebula (B) might also be the correct answer. I discounted nebula because many nebula will not form stars.</p> <p>6. I know you want “a” to be chosen, but “b” has a long history of being used in this context, too. I suggest finding a different word for “b” -- how about “corona”?</p> <p>8. I like to reverse multiple choice questions of this type—“A protostar is a star that is...”</p> <p>11. This is not a concept question – this is a vocabulary question. Why ask it? Since I didn’t see what the goal of this test was, maybe I’m misunderstanding it. But this definitely has a different flavor to it than the ADT or LPCI via vocabulary.</p> <p>13. How ‘bout “costar”? “starlet”?</p> <p>17. Students in a pre-test will choose "proto-" because of the prefix?</p> <p>18. I don’t actually like any of the answers – a protostar isn’t a “star” and the initial phase of star formation is a nebula. Couldn’t a savvy student argue that either one is correct?</p> <p>19. Since “protostar” is the only one of two answers that contains the word “star”, I’d put in more distracters. Like “red dwarf star”. Also, some of my students would argue that “nebula” (b) should be an acceptable answer. Maybe use “planetary nebula”?</p> <p>22. Although I might have to accept “b” (nebula) as correct since “as it is initially forming” is so vague. How about “just before the onset of nuclear fusion”.</p> <p>24. This is a great question!</p> <p>25. Factoid type question</p>

Item #	Comment(s)
12	<p>2. but c should be replaced with something falsier.</p> <p>3. Is there a reason that the word "gases" is present in option c? Why does it have to be gas, can it not be just "material" or "matter"?</p> <p>4. its giant nuclear furnace? ;^) "I teach the term "fusion"</p> <p>5. I, personally, prefer to emphasize the conversion of mass into energy rather than just the transmutation of elements.</p> <p>6. Option "e" does produce a very small part of the Sun's energy, if you count the decay of unstable isotopes like Be-8. Yes, I know it took energy to build it in the first place, but it does release energy when it decays.</p> <p>7. For answer "c" I'd recommend "oxidation of gases" or "gases on fire" as "burning" is a term that is used both for chemical reactions and nuclear reactions.</p> <p>8. A good way to rephrase "fusion"!</p> <p>10. From where ...</p> <p>11. This is almost identical to #8 on the ADT. Why change it? Actually, I take that back. I like the extra option. Leave it in. No – I'm guessing the ADT authors left it out for a reason... B & E are essentially the same, so leave the ADT question as is.</p> <p>16. Should you use "fusing nuclei" instead of combining atoms?</p> <p>17. Reword to emphasize fusion/fission results (also to parallel wording of question #16): (a) the combining of atoms into heavier atoms. (e) breaking apart of atoms into lighter atoms.</p> <p>18. Fine, although different nuclei are formed, not atoms.</p> <p>19. I'm from Kansas, so we would have to put in "God" as a politically correct answer. (OK, just kidding here!)</p> <p>21. I actually tell my students that the energy released originally came from the gravitational potential energy during the collapse. This goes with theme of stars representing the constant battle between gravity (order) and radiation (entropy).</p> <p>22. For the question, "Sun's energy" is vague since it includes kinetic energy, rotational etc. I think you mean "luminosity" or "energy output into space". In the possible answers, use "atomic nuclei" instead of atoms, since fusion occurs in a plasma state.</p> <p>24. Another great question!</p> <p>25. Great basic question</p>
13	<p>2. nice one</p> <p>3. High level question, much higher than the previous 12.</p> <p>5. Good question.</p> <p>13. Of the following, which ...</p> <p>11. Feels tricky. But I think it tests an important concept. Nice question!</p> <p>19. Good - I like this one!</p> <p>22. Good one!</p> <p>24. Ditto [Another great question!]</p> <p>25. Good question</p>

Item #	Comment(s)
14	<p>5. See my response to # 11. Clearly a star begins as a nebula, but not all nebula lead to stars. I feel there is a potential to confuse the student with these two questions worded as they are. [11: There is some confusion in my mind regarding this question. Nebula (B) might also be the correct answer. I discounted nebula because many nebula will not form stars.]</p> <p>8. Or d., if you're a fan of Hoyle et al. ;)</p> <p>9. Good question!</p> <p>11. Another good one, although I expect only A will get any draw. I would offer a choice: "a planet" rather than just (or perhaps instead of) "a piece of a planet". And why is "piece of a star" in there? If you want to include it, I think include it as a separate option.</p> <p>13. I find students thinking <i>everything</i> was created at the time of the Big Bang; might want a distracter choice to test for that.</p> <p>14. The answer to this question is given away by Question #6. Did you intend this?</p> <p>17. As worded, (c) "matter in the Earth's atmosphere" is arguably a subset of (a) "a piece off a star or planet." Reword (a) and (c) as new, mutually exclusive choices: (c) a piece off of another star. (d) a planet.</p> <p>18. Although technically, the process of star formation begins in the nebula. I spend so much time emphasizing the requirements for being a star – hydrostatic equilibrium and nuclear fusion – that I would hesitate to ever use this phrasing.</p> <p>19. I'm not crazy about this question. Seems like it repeats previous ideas. Also many answers can be eliminated just because they sound too kooky. At least replace answer (c) with "starlet"!</p> <p>22. Although stellar material is recycled, so "a" would be chosen by a few students who have the right idea. "a" is also a chicken+egg dilemma and not really a plausible distracter.</p> <p>25. Good basic question</p>

Item #	Comment(s)
15	<p>2. "Brightness" is ambiguous. Use "luminosity" or "absolute brightness".</p> <p>4. I don't like this question. The sun is about a 98 percentile star. That would qualify it as at the high end. (wouldn't you like to be in the 98 percentile of wage earner?) Yet on a linear scale the O stars are 10^6 times brighter! On the other hand on a logarithmic scale the sun is in the middle. Like on the HR diagrams. I don't like questions that trap the sophisticated person.</p> <p>5. This question depends (to some degree) on how you conceive brightness. If you use energy units like Watts or Solar Luminosities then the Sun is at the low end of the range. If, however, you work in absolute magnitudes, then the Sun is in the middle of the range – numerically speaking. I don't encourage the use of the term "brightness" because of the potential ambiguity between luminosity and apparent magnitude.</p> <p>6. Please, please, please do not use the word "brightness". Instead, use "luminosity". If the word "brightness" appears in the question, there is no correct answer.</p> <p>7. There is an ambiguity here. Do you mean brighter than most stars (a) or do you mean relative to the range of stellar brightness (c)?</p> <p>10. On a linear or logarithmic scale? Rated by population or brightness outer limits?</p> <p>11. I have the same comments to this question as I did to #3. However, this time my answer is different. I'm picking "average" rather than "higher than average" which I would have picked had it been available in #3. I'm not being consistent. Bad Dave! If I were consistent with my remarks in #3, I should pick "higher than avg."</p> <p>13. Near the middle on a logarithmic scale, or linear scale? Not critical difference for my high school kids, at least during a pretest phase, but might be important for college courses to differentiate these?</p> <p>16. Could you use "luminosity" instead of brightness?</p> <p>18. I would stay away from "brightness". I recognize that you inserted the parenthetical, but perhaps it would be best to phrase the question such that you don't need the parenthetical.</p> <p>19. Sorta OK. But in my class I make a clear distinction between "brightness" (a function of distance) and "luminosity" as relating to "energy output". Maybe use the word "luminosity"?</p> <p>21. The answer is "B" if you mean compared to the range of all stellar masses, but the Sun is actually more luminous than the majority of stars out there (remember, most are red dwarfs), so the answer could be "A" or "C".</p> <p>22. Argh! Brightness is NOT energy output. Please use "luminosity (rate of energy output)" instead in the stem.</p> <p>23. If a student thinks about the H_R diagram and considers magnitudes rather than brightness, they could be fooled. Maybe that's your point</p> <p>25. Somewhat ambiguous, are we talking about relative to all stars, Or on the main sequence, there can be some confusion with this question.</p> <p>26. Add (energy output, luminosity)</p>

Item #	Comment(s)
16	<p>2. I'd replace that "burning gases" phrase. The term "burning" is sometimes used in reference to fusion, as in "carbon burning phase of a post- main sequence star".</p> <p>3. Again, why is the word "gases" used in option c (2nd use of the word of course). Compare to question 12.</p> <p>4. I would like the terms "fusion" and "fission" to appear in the appropriate choices. Make a separate item to test if they know what these terms mean.</p> <p>5. See comment for # 12. [I, personally, prefer to emphasize the conversion of mass into energy rather than just the transmutation of elements.]</p> <p>6. Re: option "c": one can argue, as I did above for question 12, that fission does occur in stars, and does release energy when it occurs.</p> <p>7. Same issue as question 12. [For answer "c" I'd recommend "oxidation of gases" or "gases on fire" as "burning" is a term that is used both for chemical reactions and nuclear reactions.]</p> <p>10. Although the use of "burning" could confuse. Combustion would be better, since "burning" is often used for fusion.</p> <p>11. Some REAL sticklers would argue that D includes brown dwarfs, which I don't think you intend to do. But I don't see a way around it, and I don't think it's a real problem.</p> <p>13. As no doubt many will object, it's plasma, not gas. Though for the purpose of this test, it may be more appropriate to "keep it simple", even if not truly accurate.</p> <p>14. Most definitions of a star mention something about being "self-gravitating." Three questions (Nos. 16, 20, & 22) seem to test the same concept.</p> <p>16. Fusing nuclei as above in #12</p> <p>17. As worded, (b) "a bright point of light visible in the Earth's atmosphere" (e.g., the Sun) could arguably also be correct?</p> <p>18. Without hydrostatic equilibrium, you've also just described a fusion reactor on Earth.</p> <p>19. But conceptually very similar to question 12.</p> <p>21. I tell my students a star is a ball of gas in which gravity is precisely balanced by radiation (pressure) outward. Keep in mind fusion occurs in other places than stellar interiors (e.g. accretion disks and the Big Bang)</p> <p>22. One of 12 and 16 is redundant. As before, use "atomic nuclei" instead of atoms, since fusion occurs in a plasma state.</p> <p>25. Repetitive question, although good question for beginners, But answer B is ambiguous, need maybe to specify "within" Earth's atmosphere, otherwise could be viable answer (from)</p>
17	<p>2. You're asking for two pieces of knowledge here: color-temperature relationship and temperature-luminosity (Stefan's Law). I'd edit this to isolate the latter.</p> <p>3. High level question.</p> <p>4. I hope they learn this from the lecture-tutorial</p> <p>5. I prefer to use the phrase "appear brighter" rather than "look brighter". This preference reinforces the difference between apparent magnitude and absolute magnitude.</p> <p>8. To the human eye, I assume. Though I am sure someone somewhere will argue about "How blue? How red?"</p> <p>10. No information on potential obstructions, otherwise, it would be B</p> <p>11. Excellent question. Tests Stefan's law well.</p> <p>16. use diameter, remove the word size</p> <p>21. I like this question a lot because it combined multiple concepts.</p> <p>22. Distracter "c" is incorrectly phrased (unless the observer is color-blind!). It's hard for the eye to compare brightnesses of different colors, so it would be better to ask "which star is brighter?" than "which star looks brighter?"</p> <p>25. Actually not enough info to answer question, in that there may be intervening material. Good question on covering factors of brightness.</p>

Item #	Comment(s)
18	<p>2. good one</p> <p>5. I try not to over anthropomorphize stars by suggesting that they “live”. Myself, I would have phrased the answers as “massive stars burn...” rather than “massive stars live....”</p> <p>10. Not enough definition of relative terms (more/less and considerably/slightly)</p> <p>11. Now I see there are 3 questions about the same property of stars. Do you intend there to be 3 questions about this? That’s 12% of the test on something that takes 5 minutes to say in class and which students seem to believe readily. Seems like you’re overemphasizing it. But that might just be me.</p> <p>12. This concept is hit too many times.</p> <p>13. Though C is an appropriate answer as well, if the more massive star is only <i>slightly</i> more massive...</p> <p>14. Four questions (Nos. 5, 10, 18 & 24) all test the same concept.</p> <p>16. Confusing use of “slightly” and “considerably”?</p> <p>19. Similar to 5 and 10.</p> <p>22. Change the stem to “main sequence lifetime”</p> <p>25. Can this question be made more specific in terms of star lifetime?</p>
19	<p>2. see my note to number 15. [“Brightness” is ambiguous. Use “luminosity” or “absolute brightness”.]</p> <p>4. Could be tricky. I think for actual, physical stars, the answer is A</p> <p>5. I prefer to use the term “luminosity” rather than “energy output” or “brightness”. It is simpler (in my mind, anyway) and is unambiguous.</p> <p>6. Again, replace “brightness” with “luminosity”.</p> <p>10. I don’t know. Typically, it would be A, but I’m not sure on where WD start and PN stage ends, or on the luminosity of low mass RG stars. I’d have to look it up, I would not expect my students to be able to get this one. Isn’t energy output more closely related to luminosity than brightness?</p> <p>11. Another good question, although I see a lack of parallel-ism between choices A&B and choice C (i.e. missing “always”.) That will be noticed and will draw people’s attention. I don’t think you want to do that. But I’ve never studied “validity” or other testing lingo, so I could be completely wrong.</p> <p>14. Do you want to avoid the word “luminosity?”</p> <p>16. Confusing (did I get it right?), use of “always”, “brightness”</p> <p>17. A red giant and the Sun can have the same luminosity on an H-R diagram. A white dwarf can also have the same luminosity as a red giant and the Sun, if you include the transient evolution (diagonally down to the right) to the white dwarf pocket in the lower left-hand area of an H-R diagram.</p> <p>18. I would still consider taking out “brightness” or is it an intentional distracter?</p> <p>19. Good question. But again, I use the word “luminosity” rather than “brightness”.</p> <p>22. Again, please change “energy output (brightness)” to “rate of energy output (luminosity)”</p> <p>24. I would advocate eliminating the “brightness” from this question. Energy output is a much more appropriate phrase for what you mean.</p> <p>25. I’m not really sure of this answer</p>

Item #	Comment(s)
20	<p>3. In option "d" you mention material, whereas in question 16 and 12 you use "gases". A similar argument can be made for option "e". What is burning there?</p> <p>4. Really hitting the "burning" misconception.</p> <p>5. In my classes, I define the term "nuclear burning" as slang for nuclear reactions. In this question, my students could be confused between answers C and D.</p> <p>7. Even though the term burning is used here, I think the choice here is clearer, than in question #16 which seems to cover much the same topic.</p> <p>8. Though we often use the word "burning" to mean "fusion", which might lead some to say d.</p> <p>10. See 16 [Although the use of "burning" could confuse. Combustion would be better, since "burning" is often used for fusion.]</p> <p>11. Again it feels like you're asking the same question. But that's me – I KNOW the Sun is a star, so this question really is asking "Do you know that the Sun is a star?" when coupled with #12.</p> <p>14. Three questions (Nos. 16, 20, & 22) seem to test the same concept.</p> <p>18. I object to option "D" – we so often use the word "burning" when describing nuclear reactions, incorrect or not, that it seems inappropriate to give this option without stressing chemical burning</p> <p>21. A textbook I used before referred to "nuclear burning" so this is a good question as long as the instructor doesn't make the same mistake (or clearly state what "nuclear burning" is.</p> <p>25. Good basic question but already covered elsewhere. Helps diffuse a lot of commonly held myths by public.</p>
21	<p>4. I think the plank curve gets steeper over the optical range as T increases. But "white dwarfs" can have $T_{\text{surf}} > 100,000\text{K}$. I like the answer "patriotic"</p> <p>5. Same concern as expressed in # 7. Is white hot hotter than blue hot? It is further confused by the nomenclature of "white dwarf" that could be as hot as a B or A star which are definitely not "white hot". (Again, in my mind.)</p> <p>6. Please remove "white" from the choices, leaving only "red" and "blue."</p> <p>7. Same issue as #7, with white having a confusing place in the spectrum. Why not use red, yellow, and blue?</p> <p>11. Seems more of a concept about Wien's law rather than star properties. Do you have a distinction between a white star and a yellow star? (Not really needed for this test, but I'm guessing some teachers might use yellow instead of white because I used to, and I might still – I haven't taught stars in 2 years..)</p> <p>15. White? I never talk about white stars except to say that "these very blue, very dim stars are called white dwarfs". =) Never heard of stars that are actually 'white'. =)</p> <p>17. Rerank from coldest to hottest (left to right).</p> <p>19. Similar to 7.</p> <p>21. This question is poorly stated since "white" is NOT a color for a star, but a perceived color. The color of a star is a convolution of the blackbody spectrum of the star and the detector's sensitivity at different wavelengths. "White" is the mixture of all colors of the spectrum. If the concept you are trying to teach is the relationship between color and blackbody temperature, this is a poorly constructed question. Furthermore, to challenge a common misconception, "white dwarfs" are in fact very blue in color (just look at http://www.sdss.org/news/releases/wddm_binary.jpg for an example spectrum). I would use red, yellow, and blue, but NOT "white".</p> <p>24. But d is almost as good an answer.</p>

Item #	Comment(s)
22	<p>6. Option “c” is a correct statement: gas in the Sun will heat up if compressed. Option “d” is also a correct statement. Option “e” is also a correct statement. Finally, haven't there been enough “fusion vs. fission” questions already?</p> <p>7. Same issue as before with burning and “b” doesn’t specify nuclear reactions, could be hydrogen and oxygen combining to produce water and energy.</p> <p>8. Though some may choose a., thanks to the multivalued meaning of “burning”.</p> <p>10. Haven’t we already had this one?</p> <p>11. This, I think, is too similar to #12. I would expect you to have more than enough different concepts to test on, and this one is on here 2-3 times. I think students WILL correlate answers to this with #12. If I’m wrong, please let me know.</p> <p>12. Repeat of #12?</p> <p>13. (1) I assume it’s deliberate that the same concepts appear several times in questions that appear to be different...(2) Perhaps “the <i>surface</i> of our planet”; not the interior?</p> <p>14. Three questions (Nos. 16, 20, & 22) seem to test the same concept.</p> <p>16. nuclear fusion?</p> <p>18. Once again, please stress chemical burning. I also try to steer away from using “light elements” and use “less massive elements” – some students at this point in the semester are thinking EM radiation every time we say “light”</p> <p>19. Several questions are similar to this. Maybe you are intending to do this to check from several different conceptual angles?</p> <p>22. Redundant with question 20, and possibly 12 and 16.</p> <p>25. Repetitive questions</p>
23	<p>2. good one</p> <p>5. Good Question</p> <p>8. Though some will quibble along the lines of “Is the large red larger than the large blue?”</p> <p>9. Hard question!</p> <p>10. How does the large red star compare in size to the large blue star?</p> <p>11. Energy is a poor choice. Power might be better, or brightness or ... Energy could be interpreted by stickler scientists as “time integrated power output over the lifetime of the star” which is hard to answer. Seems like an easy fix to appease the sticklers.</p> <p>12. Repeat of question 5? [NOTE: COULD THIS BE IN REFERENCE TO QUESTION #24 INSTEAD? WAS LISTED WITH 23 BUT...]</p> <p>14. Both answers B & D would give off the most energy. An O dwarf (V) and an M supergiant (I) are at about the same luminosity. [from email: I think Q. 23 must be changed.]</p> <p>16. confusing</p> <p>18. The answer to this question would be completely different if limited to main-sequence stars. Might want to be more specific.</p> <p>19. Students might ask “But what if answer b, a “large red star” is like “really, really LARGE!!”. Then it could be the correct answer. You may need some way to constrain these answers so that “d” is the only possible correct one.</p> <p>22. “give off the most energy”. Do you mean per second, or over the lifetime of the star? (Small red stars live longer so a student may plausibly feel that it gives off the most energy over its lifetime. I’m not exactly sure I know the answer to that!).</p>

Item #	Comment(s)
24	<p>2. deja vu all over again?</p> <p>3. See comments question 5. [Using 2 and 4 creates an extra variable, the number 4, that is not used in the choices. I would prefer comparing the mass of a star directly to the Sun instead of to another star that has a different mass than the Sun.]</p> <p>4. Much better worded than the other question</p> <p>5. Even though I don't like to picture stars as "living" it is hard to avoid the "lifetime" term. I try to qualify the "lifetime" of a star by explicitly stating "main sequence lifetime".</p> <p>6. This is the same as question 5. Why ask the same question twice??</p> <p>10. We've already had similar questions</p> <p>11. The same topic comes up a 4th time! Wow. This is VERY different from the ADT or LPCI. I don't recall seeing much duplication on either of those exams. Here there is duplication all over the place. If that's intentional and for validity or soundness, great. If not, I don't understand.</p> <p>13. This question, being more specific, addresses point from #18; might even want to say "...considerably more than three times..."?</p> <p>14. Four questions (Nos. 5, 10, 18 & 24) all test the same concept.</p> <p>16. See comments above #5 [Is the mathematical relationship for lifetime and mass important for the students to know?]</p> <p>18. I know it's a bias of mine, but I think every math-phobic kid just went into a brain-freeze and you'll never know if you tested the concept or not.</p> <p>19. Good question ...but it has been asked before. I sorta prefer this one to others.</p> <p>21. This question is one that also struck me more as a test of the ability to parse English rather than the ability to understand the relationship between mass and lifetime.</p> <p>22. Redundant with question 5. Again, remove the Sun as the comparison and just have "star Y is 3 times the mass of star Z". Again avoid using labels "A" and "B since it confuses the stars' names with possible letter responses.</p> <p>25. Just like question 5. Similar comments, leave out the Sun.</p>
25	<p>2. but composition does play a role, so I'd at least say "virtually all" instead of "all".</p> <p>4. I don't think you should use "composition" as a distracter. Composition does affect a star's future. Especially with the work going on regarding the very first generation of "no metal" stars. Also re: the confusion Pop I and Pop II Cepheids caused Hubble</p> <p>5. Good Question</p> <p>6. Poor choice of wording, "all characteristics". If you change "all" to "most", then I'll answer "e" with confidence.</p> <p>8. Though I can hear the complaints about composition (d.) having an effect too.</p> <p>10. [E] Is the best answer, but is not true. Not all stars of a particular mass will go through exactly the same events.</p> <p>11. I have asked this question, and I don't like it. The reason is that if students assume you mean the "Main Sequence" radius or Main Sequence surface temperature, then all answers are equivalent as much as they can be. (Composition plays a small role in all properties – pop I vs. II vs. III.) I think the best and perhaps only way to word this is to exclude the possibility of Main Sequence values, mass loss, and to ask for the dominant characteristic. It's supposed to be a simple question, but students have caught me with technicalities that I don't think I've overcome yet.</p> <p>13. Though that's overstating the case: composition <i>does</i> affect it, as well as environment (e.g. are there massive O stars in the stellar nursery that will evaporate it before it reaches true star status?)</p> <p>18. Primarily mass, but chemical composition plays a role, too – Pop I vs Pop II vs Pop III stars. Mass, however, is the leading reason.</p> <p>19. Might be best to constrain this to "solitary or single stars", as binaries complicate the picture. Only a few science major students would pick up on this conflict however.</p> <p>21. I want to note that stellar composition does play a role in some of the characteristics and future events of a star's life. I would rephrase this to say "Which of the following plays the dominant role in determining characteristics and future events of a star's life?"</p> <p>22. Both d and e are true (Vogt-Russell theorem), and the question does not say "Which ONE of the following...?", so a student is allowed to choose more than one. Was this your intention?</p>

Item #	Comment(s)
26	<ol style="list-style-type: none"> 1. I thought this wording is ambiguous; “middle” could mean average of possible diameters, or it could mean the mode of observed stellar diameters, or the median diameter. 3. I presume you mean MS stars here, not red giants or white dwarfs. 4. Again, the Sun’s 98 percentile, so it’s bigger than 98% of the main seq. stars = A. But there are bloated monsters larger than Mar’s orbit so the answer is B. But in the HR diagram w/ radii the answer (log-speaking) is C. 5. I felt some confusion in answering this question for the following reason. The range of main sequence stellar radii is between 10 and 0.1 which would put the Sun near the smaller end of the main sequence stellar size. However, 85% of the main sequence stars are K and M stars and, therefore, smaller than the Sun in radius. According to the number-weighted average size, the Sun is on the larger end of the scale. I haven’t even brought in the giant stars yet. 7. Same issue as #15. Do you mean compared to most stars (a) or to the range of diameters (b)? 10. See 15 [On a linear or logarithmic scale? Rated by population or brightness outer limits?] 11. I have the same comments as I did for #15. [I have the same comments to this question as I did to #3. However, this time my answer is different. I’m picking “average” rather than “higher than average” which I would have picked had it been available in #3. I’m not being consistent. Bad Dave! If I were consistent with my remarks in #3, I should pick “higher than avg.”] 13. Again, depends on whether talking linear scale. Sun usually stated to be “in the middle” of the range, but much closer in absolute numbers to the size of a red dwarf than it is to size of, say, a blue supergiant 18. We typically describe the Sun as an average star, but I bet if you showed students a full range of stellar sizes w/RG, SG, they could justify calling the Sun a small star. They recall the “bigness” of the giants more than the “smallness” of the WD. Just me being picky. 19. C is the answer if you just look at the H-R diagram. But statistically our sun is 90 percentile in mass ... and pretty much in physical diameter (few are giants etc), so “a” might be a valid answer. I would rephrase the question something like “ In terms of the entire range of star sizes (diameters), it would be most accurate to say that our Sun is” 23. Could be tricky because I teach the Sun is an average star. Its diameter is near the mean. But it is on the small end if considering the range of possible stellar diameters. 25. Very ambiguous...are we talking about relative size, or comparison to total number of stars: relatively small star but a fairly common dwarf. Similar ambiguity to question 15.
<p>The following questions are asked so that I can accurately describe the volunteer reviewers. Please type your answer below.</p>	

Item #	Comment(s)
27	<ol style="list-style-type: none"> 1. Ph.D. 2. Ph.D. 3. Master of Science 4. Ph. D 5. PhD 6. Ph.D. 7. Ph.D. 8. Dad. Well, o.k., PhD. 9. Ph.D. 10. PhD 11. Masters of Science 12. Ph.D. 13. MA 14. Ph.D. 15. Masters 16. Ph. D. 17. PhD 18. Ph.D. 19. PhD Candidate (all done but final thesis approval, expected shortly) 20. MS 21. Ph.D. 22. Ph.D. 23. PhD 24. PhD 25. None. Left University in junior year after completing most math/science requirements. Mostly self taught in astrophysics. Learned to produce programs and to do technical teaching while working in transportation industry. 26. Master
28	<ol style="list-style-type: none"> 1. European History 2. physics (solid state experimental) 3. Astronomy 4. Physics 5. Planetary Science/Astronomy 6. Astronomy 7. Astronomy 8. Astronomy 9. The Ph.D. is in Curriculum and Instruction for geology. I have a MS in Aeronomy and Planetary Atmospheres 10. Astrophysics 11. Astronomy 12. Physics 13. Education (physics, math, earth science certified) 14. Astronomy 15. Astronomy 16. Physical Chemistry 17. Physics, solid state, surface science, diffraction holography of atoms. 18. Physics, specialty being astrophysics (ISM). 19. Astronomy education 20. Astronomy 21. Astrophysics 22. Astronomy 23. Physics 24. Astronomy 25. Started in Electrical Engineering, then switched to Industrial Engineering 26. Physics

Item #	Comment(s)
29	<ol style="list-style-type: none"> 1. Public High School and also as an Adjunct at a four –year college 2. community college 3. Four-year university 4. Four-year, full-time faculty 5. Community College (2 –yr) 6. Four-year university 7. I've worked at 4-year universities, planetariums, and an NSF astronomical research center. 8. 4y University 9. 4-year University 10. 4 year 11. Community college (2-yr) 12. CC 13. Public high school 14. four-year university 15. Four-year university 16. Community College 17. Community college 18. community college 19. 4 year university 20. Community college 21. four-year university 22. 4-year and community college 23. Four-year university 24. Four-year university 25. Technically I work for myself, but in affiliation with 4-year institution. 26. University College, Canada

Item #	Comment(s)
30	<ol style="list-style-type: none"> 1. I taught astronomy for the first time this year. 2. I've been teaching introductory astronomy for 4 years. 3. Have taught college level introductory astronomy for non-science majors for 3 semesters. Currently teaching introductory astronomy for non-science majors as well. 4. I teach a one-semester Intro. Astro. Every fall. 5. I have taught Introductory Astronomy to (mostly) non-science majors for the last ten years. 6. Undergraduate courses in a university, for 8 years now 7. I have taught and am currently teaching introductory astronomy at the college level. I've taught for over 30 years. 8. Taught 5y undergraduate (both intro and advanced) so far, as well as public talks. 9. I have taught astronomy for 10 years (high school) and 23 years (college setting). 10. Yes. Introductory college / high school level (concept based, minimal math). 2 courses, solar system and stars & galaxies. On and off for 7 years. 11. I have taught astronomy and physics full-time for 5 years at a community college. I've been about 50-50 in physics and astronomy. I taught only stars for 2.5 years and only planets for the last 2.5 years. I will restart stars this upcoming semester. 12. Yes, "101", 25 years. Mostly teaching physics now. 13. This year I will be teaching a one-semester astronomy course, geared towards high school juniors, primarily those with fairly weak science background. I taught it last year for first time. 14. YES; introductory college level for non-science majors for 9 years + 4 years as a TA 15. I've TA'd many times in introductory astro classes, twice in an undergrad observing class, and I'm currently teaching my first class as the instructor. 16. I have taught introductory Astronomy off and on for about 20 years. 17. Descriptive (general education requirement) introductory astronomy (i.e., "Astro 101") for three years. 18. I have been teaching AST 111/112/113/114 (introductory two semester sequence plus lab) for six years. 19. 9 years – introductory astronomy only. 20. Yes, for six years for undergraduate gen ed level courses 21. I have taught undergraduate astronomy for 6 years. The courses have ranged from 1XX level introductory astronomy review courses to 4XX level courses on extragalactic astronomy and cosmology. 22. Astro 101: 3 years. Gravitational collapse/cosmology: 1 year. 23. Yes, Intro Astronomy for three year 24. Yes, Astro 101 every semester for the last five years. 25. I've taught astrophysics for the past 15 years, as an outreach rover mostly in K-12 classrooms statewide, and some Community College and University courses. Outreach to over 300 classrooms/year, close to 8000 students, with an interactive inquiry based program that uses a lot of digital technology. 26. Yes, for 2 years. Astronomy 1100 – one-semester astronomy course for non-science majors.

The following response was sent to all reviewers.

August 1, 2005

Dear Instructor,

Please let me thank you again for sharing your time and expertise with me in reviewing the Star Properties Concept Inventory (v2.5) recently. I was overwhelmed by the positive response and the many helpful comments from all of the reviewers.

I thought it might interest you to know what major issues came up in the comments, and what was done about them. I won't go through the concept inventory question-by-question, but rather will summarize the main points.

1. Many of you noticed the apparent redundancy of some of the questions. Yes, this was intentional. In test construction, one way of establishing the reliability of questions is comparing answers to questions that get at the same content. In order to reduce random error, measurements should be stable over a variety of conditions – or in this case, over multiple questions on the same topic. More information on this topic can be found in sections on error measurement and reliability in books such as (but certainly not limited to) Nunnally (1978).¹
2. The original idea for this inventory was to focus on star formation, although it rapidly became apparent that you can't ask how stars form unless you know what stars are – thus the inclusion of many more definitional and properties-oriented questions. As iterations ensued, the formation questions actually took a back seat to properties. We have deliberately avoided stellar end states and more evolution-based questions. (After all, I need a post-doc project!)
3. Because the intention of this project is that the concept inventory would be used as a pre/post evaluation of instruction on the topic of stars, it intentionally avoids the use of many vocabulary terms that would be unfamiliar to students at the start of a course. However, it became clear upon reevaluation of some questions that this was not going to be possible. The biggest change here was of the phrase “brightness (energy output) OR energy output (brightness)” to “energy output (luminosity).”
4. Some of the distracters are not accurate science, and I recognize that. In most cases such distracters have been taken directly from student responses when asked these questions in open-ended format. Two examples: the phrase “gravity contracts,” where students have the idea of gravity as “stuff” (misunderstanding of heat is often similar) and the color white for stars. White will be a very

¹ Nunnally, J. 1978. *Psychometric theory*. New York: McGraw-Hill.

attractive distracter for students pre-instruction. If they truly understand the idea that white is a combination of all colors of light (or if instructors successfully differentiate why stars might appear white despite their peak temperature), this will not be a problem post-instruction.

5. A couple of reviewers suggested that the more “mathy” questions need not refer to the Sun, and we agreed. Instead of phrases like “Star A is 2 times the mass of the Sun and star B is 4 times the mass of the Sun,” we have used “Star B is twice as massive as star A.” Other language has been adjusted in these questions for clarity as needed.

In case you’re interested, I had 26 reviewers return comments. Of these, 19 hold Ph.D.’s and 6 hold Masters’ degrees. Twelve of the highest degrees received are in astronomy/astrophysics with another seven in physics. Reviewers teach at four-year institutions (16), community colleges (8), and public high schools (2). They have been teaching for anywhere between 1 and 30 years.

Again, thank you for your interest and your time.

Sincerely,

Janelle

Janelle M. Bailey
Ph.D. Candidate
jbailey@as.arizona.edu

APPENDIX J

STAR PROPERTIES CONCEPT INVENTORY, VERSION 3

Star Properties Concept Inventory
Version 3

1. When a star is first formed, it is made mostly of which of the following?
 - a. oxygen
 - b. nitrogen
 - c. carbon
 - d. helium
 - e. hydrogen

2. Which of the following causes a star's interior temperature to increase during its formation?
 - a. Nuclear fusion causes gravitational collapse, which generates heat.
 - b. Heat is generated when the star's gravity contracts.
 - c. Gravitational collapse involves the generation of heat from chemical reactions.
 - d. During collapse, gravitational potential energy decreases while its temperature increases.

3. The Sun's surface temperature is
 - a. near the high end of the range of surface temperatures.
 - b. near the low end of the range of surface temperatures.
 - c. near the middle of the range of surface temperatures.
 - d. about the same as the surface temperatures of all other stars.

4. During the majority of a star's existence, in which part of a star is its energy produced?
 - a. radiative layer
 - b. nucleosphere
 - c. core
 - d. throughout the star
 - e. on the surface

5. Star Y has twice the mass of star X. How will star X use up its fuel compared to star Y?
 - a. Star X will use up its fuel more than two times slower than star Y.
 - b. Star X will use up its fuel two times slower than star Y.
 - c. Star X will use up its fuel at the same rate as star Y.
 - d. Star X will use up its fuel two times faster than star Y.
 - e. Star X will use up its fuel more than two times faster than star Y.

6. The force that dominates the formation of a star is
 - a. static electricity.
 - b. gravity.
 - c. magnetism.
 - d. pressure.
 - e. nuclear fusion.

7. The hottest stars are what color?
 - a. red
 - b. white
 - c. blue
 - d. all stars have the same color regardless of their temperature
 - e. all stars have the same temperature regardless of their color

8. Why don't most stars collapse in on themselves under gravity's influence?
 - a. Material churning in and out of the center of the star balances gravity.
 - b. The internal structure of the star holds the surface out and keeps it from collapsing.
 - c. Gravity from planets orbiting the star pulls outward on the star's material.
 - d. The force from particles ejected outward from the center of the star balances gravity.
 - e. Gas pressure caused by energy created in the star pushes outward to balance gravity.

9. Which of the following objects has the highest surface temperature?
 - a. a typical red giant
 - b. a typical white dwarf
 - c. the Sun
 - d. These objects could have the same temperature.

10. Star C has a lifetime of 50 million years, while star D has a lifetime of only 10 million years. What can you say about the masses of these stars?
- Star C has the greater mass.
 - Star D has the greater mass.
 - Stars C and D have about the same mass.
 - There is not enough information given to answer this question.
11. What is the name given to a star as it is initially forming?
- protostar
 - nebula
 - supernova
 - star cluster
 - white dwarf
12. How does the Sun produce the energy that heats our planet?
- The gases inside the Sun are burning and producing energy.
 - Atoms are combined into heavier atoms, giving off energy.
 - Gas inside the Sun heats up when compressed, giving off energy.
 - Atoms are broken apart into lighter atoms, giving off energy.
 - The core of the Sun has radioactive atoms that give off energy as they decay.
13. Which of the following objects is most massive: a red giant, a white dwarf, or the Sun?
- A red giant is always the most massive.
 - A white dwarf is always the most massive.
 - The Sun is the most massive.
 - These objects could have the same mass.
14. Stars begin life as
- a piece off of a star or planet.
 - a white dwarf.
 - matter in Earth's atmosphere.
 - a black hole.
 - a cloud of gas and dust.

15. What is a star?
- a ball of gas that reflects light from another energy source
 - a bright point of light visible in Earth's atmosphere
 - a hot ball of gas that produces energy by burning gases
 - a hot ball of gas that produces energy by combining atoms into heavier atoms
 - a hot ball of gas that produces energy by breaking apart atoms into lighter atoms
16. If a red star and a blue star have the same size (diameter) and are at the same distance from Earth, which one will appear brighter?
- the red star
 - the blue star
 - Both stars will look the same.
 - There is not enough information given to answer this question.
17. How is the lifetime of a star related to its mass?
- More massive stars live considerably longer lives than less massive stars.
 - More massive stars live considerably shorter lives than less massive stars.
 - More massive stars live slightly shorter lives than less massive stars.
 - More massive stars live slightly longer lives than less massive stars.
 - All stars have the same lifetimes regardless of mass.
18. Which of the following objects has the greatest actual brightness (luminosity): a red giant, a white dwarf, or the Sun?
- A red giant always has the greatest actual brightness (luminosity).
 - A white dwarf always has the greatest actual brightness (luminosity).
 - The Sun always has the greatest actual brightness (luminosity).
 - These objects could have the same actual brightness (luminosity).
19. The light from stars that we see on Earth results from
- reflection of sunlight.
 - chemical reactions inside the stars.
 - nuclear reactions inside the stars.
 - burning of gases inside the stars.
 - burning on the surfaces of the stars.

20. How would you rank the surface temperatures of red, white, and blue stars?

	<i>Hottest</i>		→		<i>Coldest</i>
a.	white	>		blue	> red
b.	white	>		red	> blue
c.	red	>		blue	> white
d.	blue	>		white	> red
e.	blue	>		red	> white

21. Which of the following would most likely give off the most energy?

- a. a red star half the size (diameter) of the Sun
- b. a red star 10 times the size (diameter) of the Sun
- c. a blue star half the size (diameter) of the Sun
- d. a blue star 10 times the size (diameter) of the Sun

22. Star P has three times the mass of star Q. How will the lifetime of Star Q compare to the lifetime of star P?

- a. Star Q's lifetime will be less than one-third as long as that of star P.
- b. Star Q's lifetime will be one-third as long as that of star P.
- c. Star Q's lifetime will be the same as that of star P.
- d. Star Q's lifetime will be three times as long as that of star P.
- e. Star Q's lifetime will be more than three times as long as that of star P.

23. Which of the following determines most characteristics and future events of a star's existence?

- a. surface temperature
- b. size (diameter)
- c. color
- d. composition (type of atoms)
- e. mass

24. What is your gender?

- a. Female
- b. Male

25. Have you previously taken an astronomy course? (If you are taking this survey in an astronomy course, do NOT count it in your response.)

- a. Yes
- b. No

APPENDIX K

FREQUENCY OF RESPONSES BY ASTRO 101 STUDENTS ON SPCI VERSION 3,
POSTTEST

Note. N = 417. Responses in bold are the correct response.

Item	N	%
1. When a star is first formed, it is made mostly of which of the following?		
a. oxygen	10	2.4
b. nitrogen	31	7.4
c. carbon	28	6.7
d. helium	41	9.8
e. hydrogen	307	73.6
2. Which of the following causes a star's interior temperature to increase during its formation?		
a. Nuclear fusion causes gravitational collapse, which generates heat.	245	58.8
b. Heat is generated when the star's gravity contracts.	43	10.3
c. Gravitational collapse involves the generation of heat from chemical reactions.	62	14.9
d. During collapse, gravitational potential energy decreases while its temperature increases.	67	16.1
3. The Sun's surface temperature is		
a. near the high end of the range of surface temperatures.	85	20.4
b. near the low end of the range of surface temperatures.	85	20.4
c. near the middle of the range of surface temperatures.	221	53.0
d. about the same as the surface temperatures of all other stars.	26	6.2
4. During the majority of a star's existence, in which part of a star is its energy produced?		
a. radiative layer	17	4.1
b. nucleosphere	18	4.3
c. core	334	80.1
d. throughout the star	32	7.7
e. on the surface	16	3.8
5. Star Y has twice the mass of star X. How will star X use up its fuel compared to star Y?		
a. Star X will use up its fuel more than two times slower than star Y.	133	31.0
b. Star X will use up its fuel two times slower than star Y.	174	41.7
c. Star X will use up its fuel at the same rate as star Y.	23	5.5
d. Star X will use up its fuel two times faster than star Y.	67	16.1
e. Star X will use up its fuel more than two times faster than star Y.	20	4.8

Item	N	%
6. The force that dominates the formation of a star is		
a. static electricity.	5	1.2
b. gravity.	244	58.5
c. magnetism.	11	2.6
d. pressure.	40	9.6
e. nuclear fusion.	117	28.1
7. The hottest stars are what color?		
a. red	22	5.3
b. white	74	17.7
c. blue	311	74.6
d. all stars have the same color regardless of their temperature	10	2.4
e. all stars have the same temperature regardless of their color	0	0.0
8. Why don't most stars collapse in on themselves under gravity's influence?		
a. Material churning in and out of the center of the star balances gravity.	37	8.9
b. The internal structure of the star holds the surface out and keeps it from collapsing.	66	15.8
c. Gravity from planets orbiting the star pulls outward on the star's material.	49	11.8
d. The force from particles ejected outward from the center of the star balances gravity.	110	26.4
e. Gas pressure caused by energy created in the star pushes outward to balance gravity.	152	36.5
<i>No response</i>	3	0.7
9. Which of the following objects has the highest surface temperature?		
a. a typical red giant	99	23.7
b. a typical white dwarf	198	47.5
c. the Sun	66	15.8
d. These objects could have the same temperature.	54	12.9
10. Star C has a lifetime of 50 million years, while star D has a lifetime of only 10 million years. What can you say about the masses of these stars?		
a. Star C has the greater mass.	78	18.7
b. Star D has the greater mass.	256	61.4
c. Stars C and D have about the same mass.	9	2.2
d. There is not enough information given to answer this question.	74	17.7
11. What is the name given to a star as it is initially forming?		
a. protostar	264	63.3
b. nebula	105	25.2
c. supernova	29	7.0
d. star cluster	11	2.6
e. white dwarf	8	1.9

Item	N	%
12. How does the Sun produce the energy that heats our planet?		
a. The gases inside the Sun are burning and producing energy.	86	20.6
b. Atoms are combined into heavier atoms, giving off energy.	162	38.8
c. Gas inside the Sun heats up when compressed, giving off energy.	73	17.5
d. Atoms are broken apart into lighter atoms, giving off energy.	42	10.1
e. The core of the Sun has radioactive atoms that give off energy as they decay.	54	12.9
13. Which of the following objects is most massive: a red giant, a white dwarf, or the Sun?		
a. A red giant is always the most massive.	279	66.9
b. A white dwarf is always the most massive.	27	6.5
c. The Sun is the most massive.	41	9.8
d. These objects could have the same mass.	70	16.8
14. Stars begin life as		
a. a piece off of a star or planet.	10	2.4
b. a white dwarf.	11	2.6
c. matter in Earth's atmosphere.	9	2.2
d. a black hole.	4	1.0
e. a cloud of gas and dust.	383	91.8
15. What is a star?		
a. a ball of gas that reflects light from another energy source	20	4.8
b. a bright point of light visible in Earth's atmosphere	11	2.6
c. a hot ball of gas that produces energy by burning gases	117	28.1
d. a hot ball of gas that produces energy by combining atoms into heavier atoms	208	49.9
e. a hot ball of gas that produces energy by breaking apart atoms into lighter atoms	61	14.6
16. If a red star and a blue star have the same size (diameter) and are at the same distance from Earth, which one will appear brighter?		
a. the red star	37	8.9
b. the blue star	288	69.1
c. Both stars will look the same.	48	11.5
d. There is not enough information given to answer this question.	44	10.6
17. How is the lifetime of a star related to its mass?		
a. More massive stars live considerably longer lives than less massive stars.	57	13.7
b. More massive stars live considerably shorter lives than less massive stars.	310	74.3
c. More massive stars live slightly shorter lives than less massive stars.	38	6.7
d. More massive stars live slightly longer lives than less massive stars.	19	4.6
e. All stars have the same lifetimes regardless of mass.	3	0.7

Item	N	%
18. Which of the following objects has the greatest actual brightness (luminosity): a red giant, a white dwarf, or the Sun?		
a. A red giant always has the greatest actual brightness (luminosity).	133	31.9
b. A white dwarf always has the greatest actual brightness (luminosity).	147	35.3
c. The Sun always has the greatest actual brightness (luminosity).	70	16.8
d. These objects could have the same actual brightness (luminosity).	67	16.1
19. The light from stars that we see on Earth results from		
a. reflection of sunlight.	36	8.6
b. chemical reactions inside the stars.	38	9.1
c. nuclear reactions inside the stars.	184	44.1
d. burning of gases inside the stars.	90	21.6
e. burning on the surfaces of the stars.	69	16.5
20. How would you rank the surface temperatures of red, white, and blue stars?		
<i>Hottest → Coldest</i>		
a. white > blue > red	100	24.0
b. white > red > blue	29	7.0
c. red > blue > white	27	6.5
d. blue > white > red	205	49.8
e. blue > red > white	55	13.2
<i>No response</i>	1	0.2
21. Which of the following would most likely give off the most energy?		
a. a red star half the size (diameter) of the Sun	18	4.3
b. a red star 10 times the size (diameter) of the Sun	59	14.1
c. a blue star half the size (diameter) of the Sun	64	15.3
d. a blue star 10 times the size (diameter) of the Sun	276	66.2
22. Star P has three times the mass of star Q. How will the lifetime of Star Q compare to the lifetime of star P?		
a. Star Q's lifetime will be less than one-third as long as that of star P.	61	14.6
b. Star Q's lifetime will be one-third as long as that of star P.	82	19.7
c. Star Q's lifetime will be the same as that of star P.	40	9.6
d. Star Q's lifetime will be three times as long as that of star P.	146	35.0
e. Star Q's lifetime will be more than three times as long as that of star P.	81	19.4
<i>No response</i>	7	1.7

Item	N	%
23. Which of the following determines most characteristics and future events of a star's existence?		
a. surface temperature	27	6.5
b. size (diameter)	70	16.8
c. color	38	9.1
d. composition (type of atoms)	39	9.4
e. mass	239	57.3
<i>No response</i>	4	1.0
24. What is your gender?		
a. Female	204	48.9
b. Male	213	51.1
25. Have you previously taken an astronomy course? (If you are taking this survey in an astronomy course, do NOT count it in your response.)		
a. Yes	31	7.4
b. No	386	92.6

APPENDIX L

SAMPLE E-MAIL RECRUITMENT OF INTERVIEW VOLUNTEERS (PHASE II)

Spring 2005

Hi!

At the start of the semester, you participated in a survey project about students understanding of stars and star formation in your NATS 101 or 102 course. During this survey, you indicated that you might be willing to participate in an interview regarding your responses. Your name has been randomly selected from willing participants.

Interviews are being scheduled this week in the following time slots:

[insert times here]

If you are available for an interview during one of these slots, please respond ASAP with your preferred times. I suggest you plan for the process to take an hour, though if I can get us done faster I will! The interview will take place in either Steward Observatory or Education; I will let you know the exact room upon confirmation of your interview time.

If you are not available this week but are still interested, please let me know two day/times next week that would work for you.

If you are no longer interested in participating in this interview, please let me know so that I can remove your name from the list.

There are no costs or benefits to your participation; likewise there is no risk should you choose not to participate.

Thank you very much for your time. If you have any questions, please email me or call at 626-9480.

Janelle

APPENDIX M

INTERVIEW SUMMARIES (PHASE II)

The following are summary tables from 18 interviews conducted during the Spring 2005 semester, in order to confirm the results of the SFCI Version 1c format. Each table lists the Question, the participant's original response (from the pretest administration), his or her interview response, the reason for any major differences in concept, and the multiple choice response the participant said she or he would have chosen had she or he received Version 1a or 1b (MC Response). The tables are presented on the following pages in chronological order within a given format, as follows:

1. *Version 1c-1 (Questions 1-5)*
 - a. *Participant #439, March 9, 2005 (early afternoon)*
 - b. *Participant #201, March 9, 2005 (late afternoon)*
2. *Version 1c-2 (Questions 6-10)*
 - a. *Participant #369, March 30, 2005*
 - b. *Participant #343, March 31, 2005*
 - c. *Participant #387, April 1, 2005*
3. *Version 1c-3 (Questions 11-15)*
 - a. *Participant #098, February 28, 2005*
 - b. *Participant #785, March 1, 2005*
 - c. *Participant #271, April 1, 2005*
4. *Version 1c-4 (Questions 16-20)*
 - a. *Participant #111, March 8, 2005*
 - b. *Participant #282, March 29, 2005*
 - c. *Participant #342, March 30, 2005*
 - d. *Participant #326, March 31, 2005*
5. *Version 1c-5 (Questions 21-25)*
 - a. *Participant #575, February 25, 2005*
 - b. *Participant #649, March 7, 2005 (morning)*
 - c. *Participant #209, March 7, 2005 (afternoon)*
 - d. *Participant #539, March 11, 2005*
6. *Version 1c-6 (Questions 26-30)*
 - a. *Participant #122, February 23, 2005*
 - b. *Participant #130, April 1, 2005*

Interview with Participant #201 (Form 1c-1), March 9, 2005, 1pm

Item	Precourse Response	Interview Response	Reason for Difference?	MC Response
1. What is a star?	Honestly, I don't know, but for some reason I think that it is a burning mass of gas or debris. I know there is intense heat involved. I also think friction/gravity (etc?) are involved.	Compiled of matter/gas. Contains lots of H and He depending on what type of star – will become nova, supernova, or black hole. I'm not really sure about what types of stars, but generally I think it just depends on how the gases burn up, and how quickly the elements within it deplete and the reactions it cause.	Recent instruction in ASTRO 101 course.	B (correct)
2. Compared to the Sun, the greatest energy output (brightness) a star will ever have is how many times greater or smaller?	100 million times smaller	I'm not sure about that one. Brightness depends on how big it is, how much energy it has, and I think how close it is. I would guess that the Sun is 10 times greater than other stars.	Guessing.	A
3. In an average star, how is gravitational collapse balanced?	I don't know what a balance of gravitational collapse is, but I'm assuming it means why a star is not a "black hole." Gravitational collapse... I would assume there would have to be enough gravity in a star to hold it together, but not so much that it collapses or implodes.	In the Sun, it is balanced because although gravity pulls in, the reactions of convection are strong and it, like, balances out the gravity... Gases will escape if gravity is not strong enough, but will collapse if gravity is too weak.	No substantial difference. Added detail due to recent ASTRO 101 instruction.	A

Item	Precourse Response	Interview Response	Reason for Difference?	MC Response
4. Which fundamental property determines all characteristics and future events of a star's life?	Gravity – seems like it would determine mass. (rotation?)	Mass. Stars lose <u>some</u> mass, just in the escape of the gas. Gravity will cause the star to expand or implode depending on strength of gravity. I think probably gravity.	No substantial difference. Added detail due to recent ASTRO 101 instruction.	B
5. How is the lifetime of a star related to its mass?	The greater the mass the shorter the lifetime / inverse relationship. The more compact it is the more likely it is to “self-destruct” but if it has no mass at all I don't think it can exist.	The greater the mass of the star, the greater its lifetime because it has more fuel. Two times the mass would live twice as long.	Common sense reasoning.	D

Interview with Participant #439 (Form 1c-1), March 9, 2005, 3:30pm

Item	Precourse Response	Interview Response	Reason for Difference?	MC Response
1. What is a star?	I believe that a star is basically a Sun. I think they're synonymous. [Arrow points to #2: Guess not! ☺ I'm not sure really.]	A star is not a planet. I assume the Sun is a star. Different intensities. Not all stars have planets that orbit them. Gravitational force and large source of energy.	No substantial difference. Added detail due to recent ASTRO 101 instruction.	B (correct)
2. Compared to the Sun, the greatest energy output (brightness) a star will ever have is how many times greater or smaller?	10x smaller?	A star might have 10x less energy or brightness than the Sun. The Sun is larger, brighter, and has more energy than a star.	No substantial difference.	A
3. In an average star, how is gravitational collapse balanced?	By the surrounding matter, maybe planets, suns, etc	By its rotation or by the gravity of nearby planets, stars, or suns	No substantial difference. Added detail due to recent ASTRO 101 instruction.	E
4. Which fundamental property determines all characteristics and future events of a star's life?	Gravity, mass, density... If I had to pick one I'd say mass determines all characteristics and future events of a star's life	Mass, because... if you have less mass it would burn through it quicker and therefore its life would be less. In addition... if it was smaller or less mass, it wouldn't have as much gravitational pull, so it would determine how close it was to anything else.	No substantial difference. Added detail due to recent ASTRO 101 instruction.	A (correct)
5. How is the lifetime of a star related to its mass?	? I would imagine that the more mass a star has, the longer its lifetime. The smaller the star, the shorter the lifetime.	The smaller the mass, the shorter the life of a star.	No substantial difference.	A

Interview with Participant #369 (Form 1c-2), March 30, 2005, 4pm

Item	Precourse Response	Interview Response	Reason for Difference?	MC Response
6. What is the name given to a star as it is initially forming?	A nebula. Maybe a pre-star.	I think that would be a nebula. Like a protostar, I don't know. Probably protostar.	No substantial difference. Added detail due to recent ASTRO 101 instruction.	A
7. What will happen to the Sun in the future?	It will implode, or explode. Some kind of 'plode. It's yellow right now, then it becomes a dwarf, and sometimes a black hole. I think.	Implode, run out of fuel, collapse on itself and explode, and everything around us will explode.	No substantial difference.	B (correct)
8. The light from stars that we see on Earth results from what?	Stars are suns across the universe, err maybe galaxy. The light we see is like billions of years old, traveling at the speed of light, because it's light, get it?	The stars are like our Sun, they generate heat and light. So the light travels towards us (Earth). Light is a by-product of the energy and heat generated.	No substantial difference. Added detail due to recent ASTRO 101 instruction.	C (correct)
9. What is the range of temperatures average stars can have?	Oh man, really hot. I'd say at least 10,000,000 °F	4,000-12,000 K	Recent instruction in ASTRO 101 course.	C (correct)
10. If a red star and a blue star both have the same size (diameter) and both are the same distance from Earth, which one looks brighter in the sky? Why?	Blue, it's the 1 st stage, so its really hot and looks way brighter. A red star is almost dead, and colder, and thus less bright.	Blue star looks brighter, it is a lot hotter than the red star, and since same size, the blue is way more bright (luminosity) and abs. magnitude.	No substantial difference.	B (correct)

Interview with Participant #343 (Form 1c-2), March 31, 2005, 10am

Item	Precourse Response	Interview Response	Reason for Difference?	MC Response
6. What is the name given to a star as it is initially forming?	I don't know.	A new star.	Guessing.	C
7. What will happen to the Sun in the future?	It will blow up.	It could blow up, or maybe it would die off, eventually be extinguished. No more gases will be there, they'll just go away. It won't be hot any more.	Guessing.	A (correct)
8. The light from stars that we see on Earth results from what?	The heat coming off of them as they travel through space. ← just a guess	The light results from the star's luminosity. It could be a reflection from the Sun, I don't know.	Guessing.	A
9. What is the range of temperatures average stars can have?	I have no clue.	Thousands of degrees.	Guessing.	A
10. If a red star and a blue star both have the same size (diameter) and both are the same distance from Earth, which one looks brighter in the sky? Why?	The red star b/c the blue one blends in w/ the sky. ← just a guess	The blue star looks brighter because blue means it is hotter.	Recent instruction in ASTRO 101 course.	B (correct)

Interview with Participant #387 (Form 1c-2), April 1, 2005, 1pm

Item	Precourse Response	Interview Response	Reason for Difference?	MC Response
6. What is the name given to a star as it is initially forming?	I think that a star is called a dwarf either during the birth or death of a star.	Nebula, or maybe a pseudostar, something like that. Nebula was the gas cloud that forms a star, that's what I'm going to go with.	Recent instruction in ASTRO 101 course.	A (correct)
7. What will happen to the Sun in the future?	The sun will eventually burn out once it can't fuel it, chemical/ nuclear? reaction.	The material will run out and the star will burn out. The fuel (H, He) for fusion will run out.	No substantial difference. Added detail due to recent ASTRO 101 instruction.	A (correct)
8. The light from stars that we see on Earth results from what?	The light is the energy that is radiated by each star.	It is the energy emitted as a result of the fusion reaction.	Recent instruction in ASTRO 101 course.	C (correct)
9. What is the range of temperatures average stars can have?	5 million degrees centigrade? I just made that number up but I'm sure it's very high.	3,500 – 25,000 K	Recent instruction in ASTRO 101 course.	C (correct)
10. If a red star and a blue star both have the same size (diameter) and both are the same distance from Earth, which one looks brighter in the sky? Why?	The blue star, because it is emitting more energy.	Blue star gives off more energy because it is hotter and the same size and distance.	No substantial difference.	B (correct)

Interview with Participant #098 (Form 1c-3), February 28, 2005, 4pm

Item	Precourse Response	Interview Response	Reason for Difference?	MC Response
11. Compare the motions of planets relative to the Sun to the motions of stars relative to the Sun.	Planets are orbiting the Sun in elliptical orbits. The planets are pulled in a gravitational pull to the sun. The other stars have a strong gravitational fields they do not orbit our sun though they may orbit or have other stars orbit it.	Planets move in elliptical paths around the Sun. Stars move in circular paths as well.	No substantial difference.	B (correct)
12. Star A has a lifetime of 50 million years, while star B has a lifetime of only 10 million years. Which star has the greater mass? Why?	Star A does because there is more gases and material to burn and thus last longer were as star B has less mass and thus burns out and dies faster.	Star A has greater mass due to longer burning of material to make more elements.	No substantial difference.	D
13. What factors or properties influence how bright a star appears to us on Earth?	The distances the star is from Earth helps influence the brightness perceived from Earth.	Material in galaxy, distance, and how powerful star.	Recent instruction in ASTRO 101 course.	A (correct)
14. What kinds of objects do stars come from?	Stars come from gases and debris that are pulled together by a strong gravitationally force. I am not sure but I also believe Black Holes have something to do with star formation.	Gases in the Universe that comes together to form stars by high gravity fields.	Recent instruction in ASTRO 101 course.	B (correct)

Item	Precourse Response	Interview Response	Reason for Difference?	MC Response
15. The hottest stars are what color? Why?	Red stars because they are close to dying.	The hottest stars are, I want to say, reddish, because of their mass. Either that or, we talked about white dwarf stars. Yeah, I want to say that, instead of red.	Recent instruction in ASTRO 101 course.	B

Interview with Participant #785 (Form 1c-3), March 1, 2005, 12:45pm

Item	Precourse Response	Interview Response	Reason for Difference?	MC Response
11. Compare the motions of planets relative to the Sun to the motions of stars relative to the Sun.	The planets move around the Sun. This galaxy moves around the universe where other stars are in their own galaxies.	Planets go around the Sun. Stars, traditionally, are outside our solar system, do not go around Sun.	No substantial difference.	B (correct)
12. Star A has a lifetime of 50 million years, while star B has a lifetime of only 10 million years. Which star has the greater mass? Why?	Star A. Because it has the most gasses to burn off and will take longer to do so.	B has the greater mass, because of the lifetime of only 10 million years, it burns up a lot faster than the star of 50 million years. But maybe it is A, because it would be greater mass because it would have gases to burn off so it would take longer.	Common sense reasoning.	A
13. What factors or properties influence how bright a star appears to us on Earth?	How close it is. The Sun is not the brightest star, it's just the closest one to us.	How hot it's burning, I think, and that has to do with the different types of gases that are in the star. Also probably how close it is to Earth.	No substantial difference. Added detail due to recent ASTRO 101 instruction.	A (correct)
14. What kinds of objects do stars come from?	Gasses.	Gases that are burning, that's what the thermonuclear furnace is. It's the interior of the star that's burning and putting off radiation as heat.	No substantial difference. Added detail due to recent ASTRO 101 instruction.	B (correct)
15. The hottest stars are what color? Why?	White. Because I think of the term "white hot."	Red. Red giants – hottest. Brown dwarfs – coldest.	Recent instruction in ASTRO 101 course.	A

Interview with Participant #271 (Form 1c-3), April 1, 2005, 2pm

Item	Precourse Response	Interview Response	Reason for Difference?	MC Response
11. Compare the motions of planets relative to the Sun to the motions of stars relative to the Sun.	The planets revolve around the sun and the stars stay still.	Planets go around the Sun, orbit, rather. Stars appear to move but they don't.	No substantial difference.	A
12. Star A has a lifetime of 50 million years, while star B has a lifetime of only 10 million years. Which star has the greater mass? Why?	Star A. It has a greater lifetime so it has to burn longer.	Star A because 50 million years, because it lasts longer there must be more gas for it to burn off.	No substantial difference.	A
13. What factors or properties influence how bright a star appears to us on Earth?	Its mass and the gases it's made of.	Distance, color, size, temperature.	Recent instruction in ASTRO 101 course.	A (correct)
14. What kinds of objects do stars come from?	Gases.	Gases.	No substantial difference.	B (correct)
15. The hottest stars are what color? Why?	White Blue Red Orange [to the side] I don't know	Violet, indigo, blue - because they give off shorter wavelengths.	Recent instruction in ASTRO 101 course.	C (correct)

Interview with Participant #111 (Form 1c-4), March 8, 2005, 1:30pm

Item	Precourse Response	Interview Response	Reason for Difference?	MC Response
16. Stars are made mostly of which elements as they first form? Why?	I would guess carbon I am not sure but I think it is the most abundant element. Therefore I would guess that stars come from what is out there.	<u>Hydrogen</u> and helium, hydrogen is the most abundant element in the universe.	Mistaken on pretest, "I've always known this."	B (correct)
17. How does the Sun compare to a planet?	The Sun is in a constant state of fusion and keeps relieving gases unlike a planet which is just a mass form big enough to be a circle.	The sun is made up of gas and it is in continuous fusion converting hydrogen into helium.	No substantial difference. Added detail due to recent ASTRO 101 instruction.	E (correct)
18. Where does the Sun's energy come from?	The energy comes from the process of fusion but I don't know what fuses.	It comes from the fusion of hydrogen atoms into helium atoms.	No substantial difference. Added detail due to recent ASTRO 101 instruction.	A (correct)
19. In which part of the Sun does nuclear fusion take place? Why?	I would guess the inside because the inner gasses and middle fuse and the outside is the result.	The core of the layer right outside because that is where the most gravity is pressing hydrogen atoms into helium.	No substantial difference.	C (correct)
20. Star A has a mass of 2 solar masses and star B has a mass of 4 solar masses. How will the fusion rate of star A compare to the fusion rate of star B? Why?	<i>No response.</i>	I think Star A will fuse twice as fast as star B because star A is two times as small as star B and has greater pressure going on inside.	Common sense reasoning.	D

Interview with Participant #282 (Form 1c-4), March 29, 2005, 9am

Item	Precourse Response	Interview Response	Reason for Difference?	MC Response
16. Stars are made mostly of which elements as they first form? Why?	Carbon and hydrogen. Hydrogen because it is the simplest element in the universe.	Dust and gas – Hydrogen	Recent instruction in ASTRO 101 course.	B (correct)
17. How does the Sun compare to a planet?	The Sun is a lot bigger than a planet, a LOT bigger.	It's big, it's a star. A planet is cold, it has a lot more matter in it. A star burns – it's really hot, gives off a lot of energy.	No substantial difference. Added detail due to recent ASTRO 101 instruction.	E (correct)
18. Where does the Sun's energy come from?	The elements inside... maybe...	Ummm... the gases that it burns.	No substantial difference. Common sense reasoning.	E
19. In which part of the Sun does nuclear fusion take place? Why?	The middle, so the energy starts in the middle and then goes out.	The middle, cuz that's where it's the hottest.	No substantial difference.	C (correct)
20. Star A has a mass of 2 solar masses and star B has a mass of 4 solar masses. How will the fusion rate of star A compare to the fusion rate of star B? Why?	The fusion rate of star B will be $\frac{1}{2}$ as slow as that of star A. Since star B has more solar masses, the fusion rate will be slower.	$\frac{1}{2}$ the rate. B will "fuse" faster.	Guessing.	B

Interview with Participant #342 (Form 1c-4), March 30, 2005, 3pm

Item	Precourse Response	Interview Response	Reason for Difference?	MC Response
16. Stars are made mostly of which elements as they first form? Why?	Stars are mostly made of hydrogen and helium. These two elements are the most abundant in the universe and are the prime materials in gas clouds that are the beginnings of stars.	Hydrogen and helium, those are the two most abundant elements in the universe.	No substantial difference.	B (correct)
17. How does the Sun compare to a planet?	The sun is hundreds of times larger and therefore has a greater gravitational pull. It is made completely of gas, which is like some planets, but because of the inward force of gravity, it goes through a nuclear reaction that produces heat. Planets do not have a life expectancy the same way stars do and they can not "explode" the same way stars do when they go supernova.	100x more massive. Gaseous – unlike the Earth. Much more energy is given off. Nuclear fusion. Gravitational pull.	No substantial difference.	E (correct)
18. Where does the Sun's energy come from?	It comes from the nuclear fusion of hydrogen and helium.	Hydrogen and helium – fusion	No substantial difference.	A (correct)
19. In which part of the Sun does nuclear fusion take place? Why?	It takes place in the center where gravitational pressure is the greatest.	Center	No substantial difference.	C (correct)

Item	Precourse Response	Interview Response	Reason for Difference?	MC Response
20. Star A has a mass of 2 solar masses and star B has a mass of 4 solar masses. How will the fusion rate of star A compare to the fusion rate of star B? Why?	Star B will have a greater rate of fusion because it has more “fuel” since it is larger. This greater mass allows for a larger volume of fusion to take place.	B will run out of elements faster because it is bigger	No substantial difference.	B

Interview with Participant #326 (Form 1c-4), March 31, 2005, 9am

Item	Precourse Response	Interview Response	Reason for Difference?	MC Response
16. Stars are made mostly of which elements as they first form? Why?	Hydrogen (for fusion purposes?), iron.	Hydrogen (to burn), pieces of planets (collected together).	No substantial difference. Added detail due to recent ASTRO 101 instruction.	B (correct)
17. How does the Sun compare to a planet?	It is much, much bigger, perhaps millions of times bigger. Does not follow an elliptical orbit as do planets. Will eventually die out.	Much larger. Does not orbit. Gas, creating energy. Not the same types of objects – more energy production in the Sun.	No substantial difference. Added detail due to recent ASTRO 101 instruction.	E (correct)
18. Where does the Sun's energy come from?	The Sun's energy comes from nuclear fusion, which is the combining of two small atoms (such as hydrogen) into one form, the result of which is mass amounts of energy.	Fusion of hydrogen molecules, the combining of two molecules to make a new one. Maybe fission, I'm not sure. It comes from the chemical interactions of atoms and molecules. Gas, burning of gas, hydrogen molecules.	No substantial difference. Added detail due to recent ASTRO 101 instruction.	A (correct)
19. In which part of the Sun does nuclear fusion take place? Why?	In the core, atoms must have sufficient energy to be able to undergo nuclear fusion.	Core, most energy active. Energy starts at center and dissipates outward.	No substantial difference.	C (correct)
20. Star A has a mass of 2 solar masses and star B has a mass of 4 solar masses. How will the fusion rate of star A compare to the fusion rate of star B? Why?	The fusion rate of star A will be much larger because smaller masses mean quicker energy production/consumption. Inverse relationship?	Star B has higher fusion rate, more mass = more collisions in given time.	Guessing.	C

Interview with Participant #575 (Form 1c-5), February 25, 2005, 1pm

Item	Precourse Response	Interview Response	Reason for Difference?	MC Response
21. Compare how we see light from stars to how we see light from planets.	The light from stars is brighter, and looks more like a light in comparison to the light we see from planets. The light from planets seems to glow and have more shape.	Light from stars is emitted from themselves whereas light emitted from planets is light from the Sun.	Recent instruction in ASTRO 101 course.	B (correct)
22. What are molecular clouds?	Clouds formed due to chemicals.	Shapes of clouds, or caused by chemicals or gases.	Guessing.	D
23. Arrange the following stars by surface temperature from hottest to coldest: white stars, blue stars, and red stars. Why did you choose the order that you did?	Red stars, blue stars, white stars. Red normally means hot, no idea.	Red, white, blue. Red being hottest because color, blue being least because maybe it's a dead star.	Guessing.	A
24. Star A has a mass of 5 solar masses and Star B has a mass of 10 solar masses. How will the total lifetime of Star A compare to the total lifetime of Star B? Why?	A will die quicker because it has less mass.	B will last longer... [changes mind] Star A will live longer, because Star B is bigger, meaning it's older.	Guessing.	A
25. What is the force that dominates the collapse of the gas and dust in a region that may eventually form a star?	A black hole.	Black hole.	No substantial difference.	E

Interview with Participant #649 (Form 1c-5), March 7, 2005, 10am

Item	Precourse Response	Interview Response	Reason for Difference?	MC Response
21. Compare how we see light from stars to how we see light from planets.	Light from stars is created by the burning gases that make stars. The light from planets is the reflection from the sun.	Stars produce their own light while planets reflect the light from the Sun.	No substantial difference.	B (correct)
22. What are molecular clouds?	Molecular clouds are what make up the gases that burn that we see as stars... I think!	I'm not exactly sure but I think it has to do with the nucleus and the positive and negatively charge ions that surround it.	Guessing.	B
23. Arrange the following stars by surface temperature from hottest to coldest: white stars, blue stars, and red stars. Why did you choose the order that you did?	White stars, red stars, blue stars. I'm not sure but I remember learning somewhere that white stars were the hottest.	Blue stars, red stars, white stars. Blue is the hottest in the light spectrum, red comes after and then white light.	Recent instruction in ASTRO 101 course.	E
24. Star A has a mass of 5 solar masses and Star B has a mass of 10 solar masses. How will the total lifetime of Star A compare to the total lifetime of Star B? Why?	Star B will last twice as long as Star A because it has a higher solar mass which means there is more to burn.	Star B will have twice the lifetime of Star A because it has a larger mass so there is more material to burn.	No substantial difference.	B
25. What is the force that dominates the collapse of the gas and dust in a region that may eventually form a star?	Gravity.	Gravity.	No substantial difference.	B (correct)

Interview with Participant #209 (Form 1c-5), March 7, 2005, 3pm

Item	Precourse Response	Interview Response	Reason for Difference?	MC Response
21. Compare how we see light from stars to how we see light from planets.	I've heard that the way tot tell the difference between a star and a planet is the 'twinkle' factor. If the light 'twinkles' then it's a star – if it doesn't, it's probably a plant [sic] or satellite or something else.	Stars twinkle and planets don't – just a light	No substantial difference.	B (correct)
22. What are molecular clouds?	NO CLUE → Maybe – they are what stars are before they are considered a star.	<i>No response.</i>	Guessing.	D
23. Arrange the following stars by surface temperature from hottest to coldest: white stars, blue stars, and red stars. Why did you choose the order that you did?	Blue, white, red: we covered <u>some</u> astronomy in my sophomore earth science class in high school.	White, blue, red – my sophomore year in high school, I took earth science.	Recent instruction in ASTRO 101 course.	C
24. Star A has a mass of 5 solar masses and Star B has a mass of 10 solar masses. How will the total lifetime of Star A compare to the total lifetime of Star B? Why?	I would think $\frac{1}{2}$ since half of 10 is 5. That may make too much sense, though. I'm still thinking inside of the box.	A would have $\frac{1}{2}$ the life of B since 5 is $\frac{1}{2}$ than 10	No substantial difference.	B
25. What is the force that dominates the collapse of the gas and dust in a region that may eventually form a star?	?! - energy	Gravity. Or maybe something with fusion – but that's when stars are going to die, not form, I think.	Recent instruction in ASTRO 101 course.	C

Interview with Participant #539 (Form 1c-5), March 11, 2005, 3pm

Item	Precourse Response	Interview Response	Reason for Difference?	MC Response
21. Compare how we see light from stars to how we see light from planets.	When we see light from stars <u>and</u> planets we are seeing into the past. How far into the past depends on how close the object is to us. Also, light from stars appears to blink as it is sending pulses, whereas planets appear stationary.	Stars pulsate; planets continuous light. Look into the past. Stars have greater distance than the planets.	No substantial difference.	B (correct)
22. What are molecular clouds?	Molecular clouds are the haze surrounding a nebula after a star blows up.	Clouds of gas that contain molecules that form stars, galaxies, and planets.	Recent instruction in ASTRO 101 course.	B
23. Arrange the following stars by surface temperature from hottest to coldest: white stars, blue stars, and red stars. Why did you choose the order that you did?	Red, blue, white. White stars, I believe, are the hottest stars.	Blue, white, red. Remember from chemistry that blue flames are hottest, yellow is cooler. Blue star has shortest lifespan. Red star has longest. [picture drawn]	Mistaken on pretest, "I've always known this."	D (correct)
24. Star A has a mass of 5 solar masses and Star B has a mass of 10 solar masses. How will the total lifetime of Star A compare to the total lifetime of Star B? Why?	Star A will burn out earlier because it is smaller in total solar mass.	Using the HR diagram... Star B has less of a lifetime than Star A. Red stars are smaller; less mass.	Recent instruction in ASTRO 101 course.	D

Item	Precourse Response	Interview Response	Reason for Difference?	MC Response
25. What is the force that dominates the collapse of the gas and dust in a region that may eventually form a star?	I have no idea.	Gravity.	Common sense reasoning.	E

Interview with Participant #122 (Form 1c-6), February 23, 2005, 1:30pm

Item	Precourse Response	Interview Response	Reason for Difference?	MC Response
26. What property of stars has the smallest range of values over which it can vary? What is that range?	No idea!	I have absolutely no idea! I don't know ranges!	No substantial difference.	E
27. How does the Sun's size compare to the sizes of most stars?	Sun is the largest, I think.	Aha! I know now that the sun is <u>smaller</u> than most stars!	Recent instruction in ASTRO 101 course.	C
28. Stars A and B appear equally bright from Earth. However, star A actually gives off more light than star B. What is the relationship between the sizes of stars A and B?	Star A is larger and closer to the earth than Star B. The distance between the stars is greater than their distance from earth.	Star A is closer to Earth? So the relationship regarding size is that A is larger than B.	No substantial difference.	C
29. How does the Sun produce the energy that heats our planet?	Various gasses within it keep it going (?). The sun is an active planet and very much alive.	So, there is <u>a lot</u> of nuclear fusion type activity in the core – using hydrogen and another gas – I forgot which – which is creating a constant rumbling – water boiling type activity – that causes eruptions, and gas expulsion <u>VERY HOT!</u> And at such a great degree that we get benefit from it.	Recent instruction in ASTRO 101 course.	B (correct)

Item	Precourse Response	Interview Response	Reason for Difference?	MC Response
30. What causes a star's interior temperature to increase during its formation?	Gases are getting mixed around and it is creating some sort of combustion during the formation creating heat and increased temps.	The temperature has to increase in order for proper gasses and activity from it to create a star. The combination of various factors such as star dust, gasses create an element of great heat that I believe is the core of a star.	Recent instruction in ASTRO 101 course.	B

Interview with Participant #130 (Form 1c-6), April 1, 2005, 5pm

Item	Precourse Response	Interview Response	Reason for Difference?	MC Response
26. What property of stars has the smallest range of values over which it can vary? What is that range?	The light a star emits has the smallest range of values, because a star's mass/size and temperature can vary greatly.	Temperature, millions of K. Mass. [drawing provided]	Recent instruction in ASTRO 101 course.	E
27. How does the Sun's size compare to the sizes of most stars?	Our Sun is an average-sized star, yet it is a bit smaller than most other stars.	Average size	No substantial difference.	B (correct)
28. Stars A and B appear equally bright from Earth. However, star A actually gives off more light than star B. What is the relationship between the sizes of stars A and B?	Star A is probably much smaller than star B, and, if they appear equally bright from Earth, star A is probably farther away.	Star A is smaller than Star B.	No substantial difference.	B (correct)
29. How does the Sun produce the energy that heats our planet?	The Sun is going through nuclear fission which produces the heat of the Sun. The corona is the hottest part (outside the core) and it is probably from this that we receive our heat. Not much is known about the corona, though, including why it is so hot.	Nuclear fission. Hydrogen changing into helium.	No substantial difference.	B (correct)

Item	Precourse Response	Interview Response	Reason for Difference?	MC Response
30. What causes a star's interior temperature to increase during its formation?	A star uses its mass and density to pull materials to itself, which it burns to increase its temperature and gain more mass which draws in more materials to burn, and so on, and so on, in a circular process.	Nuclear fission gives off the energy to create heat, forming a star.	Recent instruction in ASTRO 101 course.	A

APPENDIX N

INSTITUTIONAL REVIEW BOARD APPROVAL MATERIALS

The following section includes scans of the approval letters from the University of Arizona's Institutional Review Board (IRB) in the Human Subjects Protection Program. Also included are copies of each approved (stamped) Subject's Disclaimer forms (used with the SSR surveys and with the concept inventories) and Subject's Consent Form – Interviews that were used throughout the study. These documents include:

- a. Phase I original approval letter (Project BSC B03.91 Eliciting students' pre-existing ideas about star formation and evolution), dated 29 May 2003
- b. Phase I Subject's Disclaimer, dated 29 May 2003
- c. Phase I Subject's Consent Form – Interviews, dated 29 May 2003 (2 pages)
- d. Phase I approval for changes, dated 19 August 2003
- e. Phase I Subject's Disclaimer form, dated 1 January 2004
- f. Phase I Periodic Review Form, approval dated 24 May, 2004
- g. Phase I Subject's Disclaimer, dated 24 May 2004
- h. Phase I Subject's Consent Form – Interviews, dated 24 May 2004 (2 pages)
- i. Phase I approval for changes, dated 16 August 2004
- j. Phase I Periodic Review Form, approval dated 9 June 2005
- k. Phase II original approval letter (Project BSC B04.238 Investigation of Student Understanding and Reasoning Difficulties About the Properties and Formation of Stars, dated 20 December 2004
- l. Phase II Subject's Disclaimer, dated 20 December 2004
- m. Phase II Subject's Consent Form – Interviews, dated 20 December 2004 (3 pages)
- n. Phase II approval for changes, dated 25 April 2005
- o. Phase II approval for changes, dated 15 August 2005
- p. Phase II Subject's Disclaimer, dated 15 August 2005
- q. Phase II Periodic Review Form, approval dated 5 January 2006

Human Subjects Protection Program
http://www.irb.arizona.edu

1330 N. Vine Avenue
P.O. Box 245137
Tucson, AZ 85724-5137
(520) 626-6721

29 May 2003

Janelle Bailey, M.Ed.
Advisor: Timothy Slater, Ph.D.
Department of Astronomy
Steward Observatory, Room 203
PO Box 210065

RE: **BSC B03.91 ELICITING STUDENTS' PRE-EXISTING BELIEFS ABOUT STAR FORMATION AND EVOLUTION**

Dear Ms. Bailey:

We received your research proposal as cited above. The procedures to be followed in this study pose no more than minimal risk to participating subjects. Regulations issued by the U.S. Department of Health and Human Services [45 CFR Part 46.110(b)] authorize approval of this type project through the expedited review procedures, with the condition(s) that subjects' anonymity be maintained. Although full Committee review is not required, a brief summary of the project procedures is submitted to the Committee for their endorsement and/or comment, if any, after administrative approval is granted. This project is approved effective **29 May 2003** for a period of one year.

The Human Subjects Committee (Institutional Review Board) of the University of Arizona has a current assurance of compliance, number FWA00004218, which is on file with the Department of Health and Human Services and covers this activity.

Approval is granted with the understanding that no further changes or additions will be made either to the procedures followed or to the consent form(s) used (copies of which we have on file) without the knowledge and approval of the Human Subjects Committee and your College or Departmental Review Committee. Any research related physical or psychological harm to any subject must also be reported to each committee.

A university policy requires that all signed subject consent forms be kept in a permanent file in an area designated for that purpose by the Department Head or comparable authority. This will assure their accessibility in the event that university officials require the information and the principal investigator is unavailable for some reason.

Sincerely yours,

Theodore J. Glattke, Ph.D.
Chair
Social and Behavioral Sciences Human Subjects Committee

TJG:tl
cc: Departmental/College Review Committee

Enclosures

APPROVED BY UNIVERSITY OF AZ IRB
THIS STAMP MUST APPEAR ON ALL
DOCUMENTS USED TO CONSENT SUBJECTS.
DATE: 5/27/09 EXPIRATION: 5/27/10

SUBJECT'S DISCLAIMER STAR FORMATION AND EVOLUTION

Title of Project: Eliciting Students' Pre-Existing Beliefs About Star Formation and Evolution

You are being invited to voluntarily participate in the above-titled research study. The purpose of the study is to investigate student understanding of concepts that relate to star formation and evolution. You are eligible to participate because you are enrolled in a general education science course.

If you agree to participate, your participation will involve responding to the questions on the attached survey. You may choose not to answer some or all of the questions. Your name will not appear on this survey. The survey will in no way impact your grade.

Any questions you have will be answered and you may withdraw from the study at any time. There are no known risks from your participation and no direct benefit from your participation is expected. There is no cost to you except for your time and you will not be compensated for your participation.

Only the principal investigator will have access to the information that you provide. In order to maintain your confidentiality, your name will not be revealed in any reports that result from this project.

You can obtain further information from the principal investigator, Janelle M. Bailey, Ph.D. candidate, at (520) 626-9480. If you have questions concerning your rights as a research subject, you may call the University of Arizona Human Subjects Protection Program office at (520) 626-6721.

By responding to the questions on the survey, you are giving permission for the investigator to use your information for research purposes.

Thank you.

Janelle M. Bailey, Ph.D. Candidate

APPROVED BY UNIVERSITY OF AZ IRB
THIS STAMP MUST APPEAR ON ALL
DOCUMENTS USED TO OBTAIN SUBJECTS
DATE 5/29/05 EXPIRATION: 5/29/06

SUBJECT'S CONSENT FORM - INTERVIEWS

Eliciting Students' Pre-Existing Beliefs About Star Formation and Evolution

Principal Investigator: Janelle M. Bailey, Graduate Research Assistant
Department of Astronomy, University of Arizona, 933 N. Cherry Ave., Tucson, AZ 85721

I AM BEING ASKED TO READ THE FOLLOWING MATERIAL TO ENSURE THAT I AM INFORMED OF THE NATURE OF THIS RESEARCH STUDY AND OF HOW I WILL PARTICIPATE IN IT, IF I CONSENT TO DO SO. SIGNING THIS FORM WILL INDICATE THAT I HAVE BEEN SO INFORMED AND THAT I GIVE MY CONSENT. FEDERAL REGULATIONS REQUIRE WRITTEN INFORMED CONSENT PRIOR TO PARTICIPATION IN THIS RESEARCH STUDY SO THAT I CAN KNOW THE NATURE AND RISKS OF MY PARTICIPATION AND CAN DECIDE TO PARTICIPATE OR NOT PARTICIPATE IN A FREE AND INFORMED MANNER.

PURPOSE

I am being invited to participate voluntarily in the above-titled research project. The purpose of this project is to explore what undergraduate students understand before instruction about concepts that relate to star formation and evolution.

SELECTION CRITERIA

I am being invited to participate because I am a student in a general education requirement science course (i.e., a Natural Science, NATS, course) and I am 18 years of age or older. Approximately 5-30 subjects will be enrolled in this portion of the study.

PROCEDURE(S)

If I agree to participate, I will be asked to consent to the following: one formal interview, lasting between 30 and 90 minutes. The interview will take place on the University of Arizona campus, at a time and place of my choosing. The interviews will be conducted between April 1, 2003, and June 30, 2005. The interview will be audio taped.

RISKS

There are no known risks.

BENEFITS

No direct benefit can be guaranteed. It is possible that I will more deeply consider my understanding of topics than I had done previously, and as a result may or may not come to a more complete or scientifically accurate understanding of the topics.

CONFIDENTIALITY

All information I provide for this study will be kept anonymous and treated with the highest degree of confidentiality. Audiotapes will be made available only to the Principal Investigator, Janelle M. Bailey, Graduate Research Assistant. Information on all transcripts and field notes will be identified only by an initial or a pseudonym of my choosing. The final product of this study will be a scholarly paper written in partial fulfillment of the requirements for the degree of Doctor of Philosophy. Additional products may include a published paper. In the event that transcript excerpts are used in the final report, my name will not be used, and additional information will be disguised or suppressed to hide my identity.

PARTICIPATION COSTS AND SUBJECT COMPENSATION

There are no costs involved in this study except a maximum of 90 minutes of my time. Participants will not receive monetary compensation. The researcher will receive no monetary compensation for conducting the study.

CONTACTS

I can obtain further information from the Principal Investigator, **Janelle M. Bailey, Graduate Research Assistant**, at (520) 626-9480. If I have questions concerning my rights as a research subject, I may call the Human Subjects Committee office at (520) 626-6721.

AUTHORIZATION

BEFORE GIVING MY CONSENT BY SIGNING THIS FORM, THE METHODS, INCONVENIENCES, RISKS, AND BENEFITS HAVE BEEN EXPLAINED TO ME AND MY QUESTIONS HAVE BEEN ANSWERED. I MAY ASK QUESTIONS AT ANY TIME AND I AM FREE TO WITHDRAW FROM THE PROJECT AT ANY TIME WITHOUT CAUSING BAD FEELINGS. MY PARTICIPATION IN THIS PROJECT MAY BE ENDED BY THE INVESTIGATOR FOR REASONS THAT WOULD BE EXPLAINED. NEW INFORMATION DEVELOPED DURING THE COURSE OF THIS STUDY WHICH MAY AFFECT MY WILLINGNESS TO CONTINUE IN THIS RESEARCH PROJECT WILL BE GIVEN TO ME AS IT BECOMES AVAILABLE. THIS CONSENT FORM WILL BE FILED IN AN AREA DESIGNATED BY THE HUMAN SUBJECTS COMMITTEE WITH ACCESS RESTRICTED TO THE PRINCIPAL INVESTIGATOR, JANELLE M. BAILEY OR AUTHORIZED REPRESENTATIVE OF THE ASTRONOMY DEPARTMENT. I DO NOT GIVE UP ANY OF MY LEGAL RIGHTS BY SIGNING THIS FORM. A COPY OF THIS SIGNED CONSENT FORM WILL BE GIVEN TO ME.

Subject's Signature

Date

Type or PRINT Full Name

PRINT Choice of Pseudonym

INVESTIGATOR'S AFFIDAVIT

I have carefully explained to the subject the nature of the above project. I hereby certify that to the best of my knowledge the person who is signing this consent form understands clearly the nature, demands, benefits, and risks involved in his/her participation and his/her signature is legally valid. A medical problem or language or educational barrier has not precluded this understanding.

Signature of Investigator
1/2000

Date

Human Subjects Protection Program
<http://www.hsb.arizona.edu>

1350 N. Vine Avenue
 P.O. Box 245137
 Tucson, AZ 85724-5137
 (520) 626-6721

19 August 2003

Janelle Bailey, M.Ed.
 Advisor: Timothy Slater, Ph.D.
 Department of Astronomy
 Steward Observatory, Room 203
 PO Box 210065

RE: **BSC B03.91 ELICITING STUDENTS' PRE-EXISTING BELIEFS ABOUT STAR FORMATION AND EVOLUTION**

Dear Mr. Bailey:

We received your 18 August 2003 letter and the submitted disclaimer (unmodified) and questionnaire forms D, E, and F, which will be attached to the back side of the disclaimer. Permission is requested use the disclaimer and the submitted questionnaire forms D, E, and F. These changes do not impact subject safety and do not impact the subject consent forms. Therefore, approval for these changes is granted effective **19 August 2003**.

The Human Subjects Committee (Institutional Review Board) of the University of Arizona has a current assurance of compliance, FWA00004218, which is on file with the Department of Health and Human Services and covers this activity.

Approval is granted with the understanding that no further changes or additions will be made either to the procedures followed or to the consent form(s) used (copies of which we have on file) without the knowledge and approval of the Human Subjects Committee and your College or Departmental Review Committee. Any research related physical or psychological harm to any subject must also be reported to each committee.

Sincerely yours,

Theodore J. Glutke, Ph.D.

Chair

Social and Behavioral Sciences Human Subjects Committee

TJG:pm

cc: Departmental/College Review Committee

Enclosures

APPROVED BY UNIVERSITY OF AZ IRB
THIS STAMP MUST APPEAR ON ALL
DOCUMENTS USED TO CONSENT SUBJECTS
DATE: 4/3/24 EXPIRATION: 5/29/24

SUBJECT'S DISCLAIMER STAR FORMATION AND EVOLUTION

Title of Project: Eliciting Students' Pre-Existing Beliefs About Star Formation and Evolution

You are being invited to voluntarily participate in the above-titled research study. The purpose of the study is to investigate student understanding of concepts that relate to star formation and evolution. You are eligible to participate because you are at least 18 years of age and are enrolled in a general education science course.

If you agree to participate, your participation will involve responding to the questions on the attached survey. You may choose not to answer some or all of the questions. Your name will be removed from this survey after a code number has been randomly assigned to your response. A spreadsheet connecting your name and the code number will be maintained through the semester in order to assign the same code number on a later administration of this survey near the end of the course. At that time, the spreadsheet will be destroyed. Only the principal investigator, Janelle M. Bailey, Ph.D. candidate, will have access to this spreadsheet. Your responses to this survey will in no way impact your grade.

Any questions you have will be answered and you may withdraw from the study at any time. There are no known risks from your participation and no direct benefit from your participation is expected. There is no cost to you except for your time and you will not be compensated for your participation.

Only the principal investigator, Janelle M. Bailey, Ph.D. candidate, will have access to the information that you provide. In order to maintain your confidentiality, your name will not be revealed in any reports that result from this project.

You can obtain further information from the principal investigator, Janelle M. Bailey, Ph.D. candidate, at (520) 626-9480. If you have questions concerning your rights as a research subject, you may call the University of Arizona Human Subjects Protection Program office at (520) 626-6721.

By responding to the questions on the survey, you are giving permission for the investigator to use your information for research purposes.

Thank you.

Janelle M. Bailey, Ph.D. Candidate

DUE DATE:
29 APRIL 2004

HUMAN SUBJECTS COMMITTEE
PERIODIC REVIEW FORM

APPROVAL EXPIRES:
5/29/2004

Janelle Bailey/B03.91/Astronomy/Eliciting Students' Pre-Existing Beliefs About Star Formation and Evolution

NAME OF INVESTIGATOR/PROJECT APPROVAL NUMBER/TITLE OF PROPOSAL

Human subjects approval for this activity expires on the date indicated above. Depending upon the activity status of the project, attachments may be required. Refer to IRB website (www.irb.arizona.edu) for detailed instructions. **Note:** If renewal is not granted before the expiration date, all study activities must stop at that time. If study procedures/treatment must be continued for subject safety, contact the IRB office immediately.

Activity Status – check one box only

Category A: attach items 1-13 listed on reverse

- ☒ Enrollment of new subjects in progress
☐ Enrollment not initiated, but still planned
☐ Enrollment closed to new subjects but current subjects are still undergoing study procedure or being entered into extensions and/or sub-studies

Category B: attach items 1-12 listed on reverse

- ☐ Enrollment closed, follow-up only (non-sensitive data collection via telephone contact, questionnaire and/or record review)
☐ Local data analysis only: no subject contact/no additional data collection (annual review required)

Category C: attach items 1-8 listed on reverse

- ☐ Concluded: enrollment and all participation/follow-up/local data analysis completed

Category D: no attachments required; complete and submit this form only

- ☐ Study not begun: permanent withdrawal of study

Subject Numbers (local enrollment)

If more than one study population is involved, report enrollment under number 2 of checklist (see reverse)

- a) Number of new subjects enrolled (consented) since last reporting period
b) Total number of subjects enrolled (consented) since start of project
c) Male/female ratio of total enrolled since start of project

2037

2037

unknown

Conflict of Interest Statement (COI): see COI policies at http://hpr2.admin.arizona.edu/irb/conflict_of_interest.htm

- a) Do any of the investigators serve as a speaker or consultant to the sponsor, the manufacturer, or the owner of the test article? ☐ Yes ☒ No
b) Do any of the investigators (or their family members) derive a direct or indirect benefit equity and/or royalty relationship with the sponsor, manufacturer, or owner of the test article? ☐ Yes ☒ No

If yes to either of the above, attach copy of U of A Conflict of Interest and Commitment Disclosure form.

I certify that this research will be conducted in accordance with the currently approved protocol/amendments and that no changes to procedures or study documents will be made without the knowledge/approval of the IRB.

Janelle Bailey
Signature of Principal Investigator
(required for all projects)

4/28/04
Date

[Signature] 4/29/04
Signature of Departmental Review Chair Date
(not required for considered or not begun studies)

FOR COMMITTEE USE ONLY

☒ Approve ☐ Disapprove

Subject to the following conditions: N/A.

Period of Approval: MAY 29 2004 — MAY 29 2005

[Signature]
Diana B. Archangeli, Ph.D., Co-Chair
Social and Behavioral Sciences Committee

Date Reviewed: MAY 24 2004

☒ Expedited Review ☐ Full Committee Review

APPROVED BY UNIVERSITY OF AZ IRB
THIS STAMP MUST APPEAR ON ALL
DOCUMENTS USED TO CONSENT SUBJECTS.
DATE: 05/24/05 EXPIRATION: 05/27/05

SUBJECT'S DISCLAIMER STAR FORMATION AND EVOLUTION

Title of Project: Eliciting Students' Pre-Existing Beliefs About Star Formation and Evolution

You are being invited to voluntarily participate in the above-titled research study. The purpose of the study is to investigate student understanding of concepts that relate to star formation and evolution. You are eligible to participate because you are at least 18 years of age and are enrolled in a general education science course.

If you agree to participate, your participation will involve responding to the questions on the attached survey. You may choose not to answer some or all of the questions. Your name will be removed from this survey after a code number has been randomly assigned to your response. A spreadsheet connecting your name and the code number will be maintained through the semester in order to assign the same code number on a later administration of this survey near the end of the course. At that time, the spreadsheet will be destroyed. Only the principal investigator, Janelle M. Bailey, Ph.D. candidate, will have access to this spreadsheet. Your responses to this survey will in no way impact your grade.

Any questions you have will be answered and you may withdraw from the study at any time. There are no known risks from your participation and no direct benefit from your participation is expected. There is no cost to you except for your time and you will not be compensated for your participation.

Only the principal investigator, Janelle M. Bailey, Ph.D. candidate, will have access to the information that you provide. In order to maintain your confidentiality, your name will not be revealed in any reports that result from this project.

You can obtain further information from the principal investigator, Janelle M. Bailey, Ph.D. candidate, at (520) 626-9480. If you have questions concerning your rights as a research subject, you may call the University of Arizona Human Subjects Protection Program office at (520) 626-6721.

By responding to the questions on the survey, you are giving permission for the investigator to use your information for research purposes.

Thank you.

Janelle M. Bailey, Ph.D. Candidate

APPROVED BY UNIVERSITY OF AZ IRB
THIS STAMP MUST APPEAR ON ALL
DOCUMENTS USED TO CONSENT SUBJECTS.
DATE: 05/24/07 EXPIRATION: 05/29/08

SUBJECT'S CONSENT FORM - INTERVIEWS

Eliciting Students' Pre-Existing Beliefs About Star Formation and Evolution

Principal Investigator: Janelle M. Bailey, Graduate Research Assistant
Department of Astronomy, University of Arizona, 933 N. Cherry Ave., Tucson, AZ 85721

I AM BEING ASKED TO READ THE FOLLOWING MATERIAL TO ENSURE THAT I AM INFORMED OF THE NATURE OF THIS RESEARCH STUDY AND OF HOW I WILL PARTICIPATE IN IT, IF I CONSENT TO DO SO. SIGNING THIS FORM WILL INDICATE THAT I HAVE BEEN SO INFORMED AND THAT I GIVE MY CONSENT. FEDERAL REGULATIONS REQUIRE WRITTEN INFORMED CONSENT PRIOR TO PARTICIPATION IN THIS RESEARCH STUDY SO THAT I CAN KNOW THE NATURE AND RISKS OF MY PARTICIPATION AND CAN DECIDE TO PARTICIPATE OR NOT PARTICIPATE IN A FREE AND INFORMED MANNER.

PURPOSE

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PROCEDURE(S)

If I agree to participate, I will be asked to consent to the following: one formal interview, lasting between 30 and 90 minutes. The interview will take place on the University of Arizona campus, at a time and place of my choosing. The interviews will be conducted between April 1, 2003, and June 30, 2005. The interview will be audio taped.

RISKS

There are no known risks.

BENEFITS

No direct benefit can be guaranteed. It is possible that I will more deeply consider my understanding of topics than I had done previously, and as a result may or may not come to a more complete or scientifically accurate understanding of the topics.

CONFIDENTIALITY

All information I provide for this study will be kept anonymous and treated with the highest degree of confidentiality. Audiotapes will be made available only to the Principal Investigator, Janelle M. Bailey, Graduate Research Assistant. Information on all transcripts and field notes will be identified only by an initial or a pseudonym of my choosing. The final product of this study will be a scholarly paper written in partial fulfillment of the requirements for the degree of Doctor of Philosophy. Additional products may include a published paper. In the event that transcript excerpts are used in the final report, my name will not be used, and additional information will be disguised or suppressed to hide my identity.

PARTICIPATION COSTS AND SUBJECT COMPENSATION

There are no costs involved in this study except a maximum of 90 minutes of my time. Participants will not receive monetary compensation. The researcher will receive no monetary compensation for conducting the study.

CONTACTS

I can obtain further information from the Principal Investigator, **Janelle M. Bailey, Graduate Research Assistant**, at (520) 626-9480. If I have questions concerning my rights as a research subject, I may call the Human Subjects Committee office at (520) 626-6721.

AUTHORIZATION

BEFORE GIVING MY CONSENT BY SIGNING THIS FORM, THE METHODS, INCONVENIENCES, RISKS, AND BENEFITS HAVE BEEN EXPLAINED TO ME AND MY QUESTIONS HAVE BEEN ANSWERED. I MAY ASK QUESTIONS AT ANY TIME AND I AM FREE TO WITHDRAW FROM THE PROJECT AT ANY TIME WITHOUT CAUSING BAD FEELINGS. MY PARTICIPATION IN THIS PROJECT MAY BE ENDED BY THE INVESTIGATOR FOR REASONS THAT WOULD BE EXPLAINED. NEW INFORMATION DEVELOPED DURING THE COURSE OF THIS STUDY WHICH MAY AFFECT MY WILLINGNESS TO CONTINUE IN THIS RESEARCH PROJECT WILL BE GIVEN TO ME AS IT BECOMES AVAILABLE. THIS CONSENT FORM WILL BE FILED IN AN AREA DESIGNATED BY THE HUMAN SUBJECTS COMMITTEE WITH ACCESS RESTRICTED TO THE PRINCIPAL INVESTIGATOR, JANELLE M. BAILEY OR AUTHORIZED REPRESENTATIVE OF THE ASTRONOMY DEPARTMENT. I DO NOT GIVE UP ANY OF MY LEGAL RIGHTS BY SIGNING THIS FORM. A COPY OF THIS SIGNED CONSENT FORM WILL BE GIVEN TO ME.

 Subject's Signature

 Date

 Type or PRINT Full Name

 PRINT Choice of Pseudonym
INVESTIGATOR'S AFFIDAVIT

I have carefully explained to the subject the nature of the above project. I hereby certify that to the best of my knowledge the person who is signing this consent form understands clearly the nature, demands, benefits, and risks involved in his/her participation and his/her signature is legally valid. A medical problem or language or educational barrier has not precluded this understanding.

 Signature of Investigator
 1/2000

 Date

Human Subjects Protection Program
<http://www.irb.arizona.edu>

1350 N. Vine Avenue
 P.O. Box 243137
 Tucson, AZ 85724-3137
 (520) 626-6721

16 August 2004

Janelle Bailey, M.Ed.
 Advisor: Timothy Slater, Ph.D.
 Department of Astronomy
 Steward Observatory, Room 203
 P.O. Box 210065

RE: **BSC B03.91** ELICITING STUDENTS' PRE-EXISTING BELIEFS ABOUT STAR
 FORMATION AND EVOLUTION

Dear Ms. Bailey:

We received your 6 August 2004 letter and accompanying new questionnaires for the above-cited project. Permission is requested to use questionnaire forms L, M and N for Fall 2004. As previously approved, the consenting document will be printed on the reverse side of each questionnaire. These changes do not impact subject safety nor the consenting documents. Therefore, approval of these changes is granted effective 16 August 2004.

The Human Subjects Committee (Institutional Review Board) of the University of Arizona has a current *Federalwide Assurance* of compliance, *FWA00004218*, which is on file with the Department of Health and Human Services and covers this activity.

Approval is granted with the understanding that no further changes or additions will be made either to the procedures followed or to the consent form(s) used (copies of which we have on file) without the knowledge and approval of the Human Subjects Committee and your College or Departmental Review Committee. Any research related physical or psychological harm to any subject must also be reported to each committee.

Sincerely yours,

A handwritten signature in black ink that reads "Theodore J. Glatke".

Theodore J. Glatke, Ph.D.
 Chair
 Social and Behavioral Sciences Human Subjects Committee

TJG:nm

cc: Departmental/College Review Committee

DUE DATE:
6 MAY 2005

HUMAN SUBJECTS COMMITTEE
PERIODIC-REVIEW FORM

APPROVAL EXPIRES:
5/29/2005

Janelle Bailey/B03.91/Astronomy/Eliciting Students' Pre-Existing Beliefs About Star Formation and Evolution

NAME OF INVESTIGATOR/PROJECT APPROVAL NUMBER/TITLE OF PROPOSAL

Human subjects approval for this activity expires on the date indicated above. Depending upon the activity status of the project, attachments may be required. Refer to IRB website (www.irb.arizona.edu) for detailed instructions. **Note:** If renewal is not granted before the expiration date, all study activities must stop at that time. If study procedures/treatment must be continued for subject safety, contact the IRB office immediately.

Activity Status – check one box only

Category A: attach items 1-13 listed on reverse

- ☐ Enrollment of new subjects in progress
- ☐ Enrollment not initiated, but still planned
- ☐ Enrollment closed to new subjects but current subjects are still undergoing study procedure or being entered into extensions and/or sub-studies

Category B: attach items 1-12 listed on reverse

- ☐ Enrollment closed, follow-up only (non-sensitive data collection via telephone contact, questionnaire and/or record review)
- ☒ Local data analysis only; no subject contact/no additional data collection (annual review required)

Category C: attach items 1-8 listed on reverse

- ☐ Concluded: enrollment and all participation/follow-up/local data analysis completed

Category D: no attachments required; complete and submit this form only

- ☐ Study not begun; permanent withdrawal of study

Subject Numbers (local enrollment)

If more than one study population is involved, report enrollment under number 2 of checklist (see reverse)

- a) Number of new subjects enrolled (consented) since last reporting period
- b) Total number of subjects enrolled (consented) since start of project
- c) Number of males/number of females enrolled since start of project

463
8520
unknown

Conflict of Interest Statement (COI): see COI policies at http://vpr2.admin.arizona.edu/ria/conflict_of_interest.htm

- a) Do any of the investigators serve as a speaker or consultant to the sponsor, the manufacturer, or the owner of the test article? ☐ Yes ☒ No
- b) Do any of the investigators (or their family members) derive a direct or indirect benefit, equity and/or royalty relationship with the sponsor, manufacturer, or owner of the test article? ☐ Yes ☒ No

If yes to either of the above, review COI policies to determine whether U of A Conflict of Interest and Commitment Disclosure form must be filed.

I certify that this research will be conducted in accordance with the currently approved protocol/amendments and that no changes to procedures or study documents will be made without the knowledge/approval of the IRB.

Signature of Principal Investigator
(required for all projects)

5/16/05
Date

Signature of Departmental Review Chair Date
(not required for Category C or Category D)

FOR COMMITTEE USE ONLY

☒ Approve ☐ Disapprove

Period of Approval: JUN 09 2005 — MAY 29 2006

Subject to the following conditions: N/A. Change in personnel (removing Data Analyst John Keller and Erika Offerdahl) approved concurrently.

Theodore J. Clark, Ph.D., Chair
Social and Behavioral Sciences Committee

Date Reviewed: JUN 09 2005

☒ Expedited Review ☐ Full Committee Review

Human Subjects Protection Program
<http://www.irb.arizona.edu>

20 December 2004

1350 N. Vine Avenue
 P.O. Box 243137
 Tucson, AZ 85724-5137
 (520) 626-6711

Janelle Bailey, Ph.D. candidate
 Advisor: Bruce Johnson, Ph.D.
 Department of Teaching and Teacher Education
 P.O. Box 210069

RE: BSC B04.238 INVESTIGATION OF STUDENT UNDERSTANDING AND REASONING DIFFICULTIES
 ABOUT THE PROPERTIES AND FORMATION OF STARS

Dear Ms. Bailey:

We received your research proposal as cited above. The procedures to be followed in this study pose no more than minimal risk to participating subjects and have been reviewed by the Institutional Review Board (IRB) through an Expedited Review procedure as cited in the regulations issued by the U.S. Department of Health and Human Services [45 CFR Part 46.110(b)(1)] based on their inclusion under research category 6 and 7. Although full Committee review is not required, a brief summary of the project procedures is submitted to the Committee for their endorsement and/or comment, if any, after administrative approval is granted. This project is approved with an **expiration date of 20 December 2005**. *Note: Requirement of signed informed consent has been waived for parts of this study as the research exposes the participants to no more risk than everyday life as stated in 45 CFR 46.117(c)(2).* Please make copies of the attached IRB stamped consenting documents to obtain consent from your subjects.

The Human Subjects Committee (Institutional Review Board) of the University of Arizona has a current Federal Wide Assurance of compliance, number FWA00004218, which is on file with the Department of Health and Human Services and covers this activity.

Approval is granted with the understanding that no further changes or additions will be made either to the procedures followed or to the consent form(s) used (copies of which we have on file) without the knowledge and approval of the Human Subjects Committee and your College or Departmental Review Committee. Any research related physical or psychological harm to any subject must also be reported to each committee.

A university policy requires that all signed subject consent forms be kept in a permanent file in an area designated for that purpose by the Department Head or comparable authority. This will assure their accessibility in the event that university officials require the information and the principal investigator is unavailable for some reason.

Sincerely yours,

Theodore J. Glatts, Ph.D.
 Chair,
 Social and Behavioral Sciences Human Subjects Committee

TJG:pm

cc: Departmental/College Review Committee

APPROVED BY UNIVERSITY OF AZ IRB
THIS STAMP MUST APPEAR ON ALL
DOCUMENTS USED TO CONSENT SUBJECTS.
DATE: 12/22/24 EXPIRATION: 12/22/25

SUBJECT'S DISCLAIMER STAR FORMATION CONCEPT INVENTORY

Title of Project: An Investigation of Student Understanding and Reasoning Difficulties about the Properties and Formation of Stars

You are being invited to voluntarily participate in the above-titled research study. The purpose of the study is to investigate student understanding of concepts that relate to star formation and evolution both before formal instruction in Astronomy 101 and again at the end of the course. You are eligible to participate because you are enrolled in a general education science course and are at least 18 years of age. Up to 4,000 students will be asked to participate.

If you agree to participate, your participation will involve responding to the questions on the attached "concept inventory" (questionnaire). You may choose not to answer some or all of the questions. This same questionnaire will be given to you again in May, at the end of the course. The answers you provide on this survey will in no way impact your grade.

Any questions you have will be answered and you may withdraw from the study at any time. There are no known risks from your participation and no direct benefit from your participation is expected. There is no cost to you except for your time and you will not be compensated for your participation. The questionnaire will take 10-15 minutes of class time to complete.

Only the principal investigator will have access to the information that you provide. In order to maintain your confidentiality, your name will not be revealed in any reports that result from this project.

You can obtain further information from the principal investigator, Janelle M. Bailey, Ph.D. candidate, at (520) 626-9480. If you have questions concerning your rights as a research subject, you may call the University of Arizona Human Subjects Protection Program office at (520) 626-6721.

By responding to the questions on the survey, you are giving permission for the investigator to use your information for research purposes.

Thank you.

Janelle M. Bailey, Ph.D. Candidate

APPROVED BY UNIVERSITY OF AZ IRB
THIS STAMP MUST APPEAR ON ALL
DOCUMENTS USED TO CONSENT SUBJECTS.
DATE 12/20/04 EXPIRATION 12/20/05

SUBJECT'S CONSENT FORM - INTERVIEWS

An Investigation of Student Understanding and Reasoning Difficulties about the Properties and Formation of Stars

Principal Investigator: Janelle M. Bailey, Graduate Teaching Associate
Department of Teaching and Teacher Education, P.O. Box 210069, Tucson, AZ 85721

I AM BEING ASKED TO READ THE FOLLOWING MATERIAL TO ENSURE THAT I AM INFORMED OF THE NATURE OF THIS RESEARCH STUDY AND OF HOW I WILL PARTICIPATE IN IT, IF I CONSENT TO DO SO. SIGNING THIS FORM WILL INDICATE THAT I HAVE BEEN SO INFORMED AND THAT I GIVE MY CONSENT. FEDERAL REGULATIONS REQUIRE WRITTEN INFORMED CONSENT PRIOR TO PARTICIPATION IN THIS RESEARCH STUDY SO THAT I CAN KNOW THE NATURE AND RISKS OF MY PARTICIPATION AND CAN DECIDE TO PARTICIPATE OR NOT PARTICIPATE IN A FREE AND INFORMED MANNER.

PURPOSE

I am being invited to participate voluntarily in the above-titled research project. The purpose of this project is to explore what undergraduate students understand before instruction about concepts that relate to star formation and evolution.

SELECTION CRITERIA

I am being invited to participate because I am a student in a general education requirement science course (i.e., a Natural Science, NATS, course) and I am 18 years of age or older. I have been selected because I expressed a willingness to participate in the interview when I completed a questionnaire on the first day of the NATS course. Approximately 5-30 subjects will be enrolled in this portion of the study.

PROCEDURE(S)

If I agree to participate, I will be asked to consent to the following: one formal interview, lasting between 30 and 90 minutes. The interview will take place on the University of Arizona campus in Steward Observatory, at a time of my choosing. The interview will take place within the first month of the semester in which I am enrolled in the NATS course. The interview will be audio taped.

RISKS

There are no known risks. Participation in this interview will have no impact on my grade.

BENEFITS

No direct benefit can be guaranteed. It is possible that I will more deeply consider my understanding of topics than I had done previously, and as a result may or may not come to a more complete or scientifically accurate understanding of the topics.

CONFIDENTIALITY

All information I provide for this study will be kept anonymous and treated with the highest degree of confidentiality. Audiotapes will be made available only to the Principal Investigator, Janelle M. Bailey, Graduate Research Assistant. Information on all transcripts and field notes will be identified only by an initial or a pseudonym of my choosing. The final product of this study will be a scholarly paper written in partial fulfillment of the requirements for the degree of Doctor of Philosophy. Additional products may include a published paper. In the event that transcript excerpts are used in the final report, my name will not be used, and additional information will be disguised or suppressed to hide my identity.

PARTICIPATION COSTS AND SUBJECT COMPENSATION

There are no costs involved in this study except a maximum of 90 minutes of my time. There is no compensation of any kind of participants. The researcher will receive no monetary compensation for conducting the study.

CONTACTS

I can obtain further information from the Principal Investigator, **Janelle M. Bailey, Graduate Teaching Associate**, at (520) 626-9480. If I have questions concerning my rights as a research subject, I may call the Human Subjects Protection Program office at (520) 626-6721.

AUTHORIZATION

BEFORE GIVING MY CONSENT BY SIGNING THIS FORM, THE METHODS, INCONVENIENCES, RISKS, AND BENEFITS HAVE BEEN EXPLAINED TO ME AND MY QUESTIONS HAVE BEEN ANSWERED. I MAY ASK QUESTIONS AT ANY TIME AND I AM FREE TO WITHDRAW FROM THE PROJECT AT ANY TIME WITHOUT CAUSING BAD FEELINGS. MY PARTICIPATION IN THIS PROJECT MAY BE ENDED BY THE INVESTIGATOR FOR REASONS THAT WOULD BE EXPLAINED. NEW INFORMATION DEVELOPED DURING THE COURSE OF THIS STUDY WHICH MAY AFFECT MY WILLINGNESS TO CONTINUE IN THIS RESEARCH PROJECT WILL BE GIVEN TO ME AS IT BECOMES AVAILABLE. THIS CONSENT FORM WILL BE FILED IN AN AREA DESIGNATED BY THE HUMAN SUBJECTS COMMITTEE WITH ACCESS RESTRICTED TO THE PRINCIPAL INVESTIGATOR, JANELLE M. BAILEY OR AUTHORIZED REPRESENTATIVE OF THE TEACHING AND TEACHER EDUCATION DEPARTMENT. I DO NOT GIVE UP ANY OF MY LEGAL RIGHTS BY SIGNING THIS FORM. A COPY OF THIS SIGNED CONSENT FORM WILL BE GIVEN TO ME.

 Subject's Signature

 Date

 Type or PRINT Full Name

 PRINT Choice of Pseudonym

INVESTIGATOR'S AFFIDAVIT

I have carefully explained to the subject the nature of the above project. I hereby certify that to the best of my knowledge the person who is signing this consent form understands clearly the nature, demands, benefits, and risks involved in his/her participation and his/her signature is legally valid. A medical problem or language or educational barrier has not precluded this understanding.

Signature of Investigator
1/2000

Date

Human Subjects Protection Program
<http://www.hsb.arizona.edu>

1350 N. Vine Avenue
 P.O. Box 245137
 Tucson, AZ 85724-5137
 (520) 626-0721

25 April 2005

Janelle Bailey, Ph.D. candidate
 Advisor: Bruce Johnson, Ph.D.
 Department of Teaching and Teacher Education
 P.O. Box 210069

RE: **BSC B04.238** AN INVESTIGATION OF STUDENT UNDERSTANDING AND
 REASONING DIFFICULTIES ABOUT THE PROPERTIES AND FORMATION OF
 STARS

Dear Ms. Bailey:

We received your 19 April 2005 letter and accompanying revised questionnaires for the above-cited study. Permission is requested to revise the 10 questionnaires (which measure knowledge of star formation and are randomly distributed at the beginning and end of the semester) to re-order the questions and incorporate minor language changes to increase clarity. These changes do not impact subject safety nor the consenting documents. Approval of these changes is granted effective 25 April 2005.

The Human Subjects Committee (Institutional Review Board) of the University of Arizona has a current *Federalwide Assurance* of compliance, *FWA00004218*, which is on file with the Department of Health and Human Services and covers this activity.

Approval is granted with the understanding that no further changes or additions will be made either to the procedures followed or to the consent form(s) used (copies of which we have on file) without the knowledge and approval of the Human Subjects Committee and your College or Departmental Review Committee. Any research related physical or psychological harm to any subject must also be reported to each committee.

Sincerely yours,

Theodore J. Glattke, Ph.D.

Chair

Social and Behavioral Sciences Human Subjects Committee

TJG:nm

cc: Departmental/College Review Committee

Human Subjects Protection Program
<http://www.irb.arizona.edu>

15 August 2005

Janelle Bailey, Ph.D. candidate
 Advisor: Bruce Johnson, Ph.D.
 Department of Teaching and Teacher Education
 P.O. Box 210069

1350 N. Vine Avenue
 P.O. Box 245137
 Tucson, AZ 85724-5137
 (520) 626-6721

RE: **BSC B04.238** INVESTIGATION OF STUDENT UNDERSTANDING AND REASONING
 DIFFICULTIES ABOUT THE PROPERTIES AND FORMATION OF STARS

Dear Ms. Bailey:

We received your 12 August and 15 August 2005 letters and accompanying revised surveys and consenting document for the above-cited study. Permission is requested to:

- revise procedures so that all students will complete the same version of the survey and use a scannable answer form rather than responding on the survey itself (students will include their names on the scannable form rather than the survey to match up with follow-up surveys).
- revise survey to include a new title which more accurately reflects the content of questions, delete questions based on review of data from previous administration of the survey, delete question about recruiting interview volunteers (since this portion of the study is complete), and incorporate minor language and numbering changes.
- revise approved consenting document (signature waived) to include updated survey title and clarify follow-up information.

These changes do not impact subject safety nor subject burden. Approval of these changes is granted effective 15 August 2005.

The Human Subjects Committee (Institutional Review Board) of the University of Arizona has a current *Federalwide Assurance* of compliance, *FWA00004218*, which is on file with the Department of Health and Human Services and covers this activity.

Approval is granted with the understanding that no further changes or additions will be made either to the procedures followed or to the consent form(s) used (copies of which we have on file) without the knowledge and approval of the Human Subjects Committee and your College or Departmental Review Committee. Any research related physical or psychological harm to any subject must also be reported to each committee.

Sincerely yours,

Theodore J. Glauke, Ph.D.
 Chair, Social and Behavioral Sciences Human Subjects Committee

TJG:nm

cc: Departmental/College Review Committee

Enclosure

APPROVED BY UNIVERSITY OF AZ IRB
THIS STAMP MUST APPEAR ON ALL
DOCUMENTS USED TO CONSENT SUBJECTS.
DATE: 08/10/05 EXPIRATION: 12/31/05

SUBJECT'S DISCLAIMER STAR PROPERTIES CONCEPT INVENTORY

Title of Project: An Investigation of Student Understanding and Reasoning Difficulties about the Properties and Formation of Stars

You are being invited to voluntarily participate in the above-titled research study. The purpose of the study is to investigate student understanding of concepts that relate to star formation and evolution both before formal instruction in Astronomy 101 and again at the end of the course. You are eligible to participate because you are enrolled in a general education science course and are at least 18 years of age. Up to 4,000 students will be asked to participate.

If you agree to participate, your participation will involve responding to the questions on the attached "concept inventory" (questionnaire). You may choose not to answer some or all of the questions. This same questionnaire will be given to you again at the end of the course. The answers you provide on this survey will in no way impact your grade.

Any questions you have will be answered and you may withdraw from the study at any time. There are no known risks from your participation and no direct benefit from your participation is expected. There is no cost to you except for your time and you will not be compensated for your participation. The questionnaire will take 10-15 minutes of class time to complete.

Only the principal investigator will have access to the information that you provide. In order to maintain your confidentiality, your name will not be revealed in any reports that result from this project.

You can obtain further information from the principal investigator, Janelle M. Bailey, Ph.D. candidate, at (520) 626-9480. If you have questions concerning your rights as a research subject, you may call the University of Arizona Human Subjects Protection Program office at (520) 626-6721.

By responding to the questions on the survey, you are giving permission for the investigator to use your information for research purposes.

Thank you.

Janelle M. Bailey, Ph.D. Candidate

Jan 05 08 09:00a UNIV OF ARIZ 6217877 P. 8
12/28/2005 11:51 6266721 * HUMAN SUBJECTS PROT PWE 02/09

DUE DATE:
9 DECEMBER 2005

HUMAN SUBJECTS COMMITTEE
PERIODIC REVIEW FORM

APPROVAL EXPIRES:
12/28/2005

Janelle Bailey/B04.238/Teach/Teach Edu/An Investigation of Student Understanding and Reasoning
Difficulties about the Properties and Formation of Stars
NAME OF INVESTIGATOR/PROJECT APPROVAL NUMBER/TITLE OF PROPOSAL

Human subjects approval for this activity expires on the date indicated above. Depending upon the activity status of the project, attachments may be required. Refer to IRB website (www.irb.arizona.edu) for detailed instructions and report template. Note: If renewal is not granted before the expiration date, all study activities must stop at that time. If study procedures/treatment must be continued for subject safety, contact the IRB office immediately.

Activity Status – check one box only

Category A: attach items 1-13 listed on reverse

- ☐ Enrollment of new subjects in progress
- ☐ Enrollment not initiated, but still planned
- ☐ Enrollment closed to new subjects but current subjects are still undergoing study procedure or being entered into extensions and/or sub-studies

Category B: attach items 1-12 listed on reverse

- ☐ Enrollment closed, follow-up only (non-sensitive data collection via telephone contact, questionnaire and/or record review)
- ☒ Local data analysis only, no subject contact/no additional data collection (annual review required)

Category C: attach items 1-8 listed on reverse

- ☐ Concluded: enrollment and all participation/follow-up/local data analysis completed

Category D: no attachments required; complete and submit this form only

- ☐ Study not begun; permanent withdrawal of study

Subject Numbers (local enrollment)

If more than one study population is involved, report enrollment under number 2 of checklist (see reverse)

- a) Number of new subjects enrolled (consented) since last reporting period
- b) Total number of subjects enrolled (consented) since start of project
- c) Number of males/number of females enrolled since start of project

2054
2054
957/986/171.2054.000

Conflict of Interest Statement (COI): see COI policies at http://vp2.admin.arizona.edu/irb/conflict_of_interest.htm

- a) Do any of the investigators serve as a speaker or consultant to the sponsor, the manufacturer, or the owner of the test article? ☐ Yes ☒ No
- b) Do any of the investigators (or their family members) derive a direct or indirect benefit, equity and/or royalty relationship with the sponsor, manufacturer, or owner of the test article? ☐ Yes ☒ No

If yes to either of the above, review COI policies to determine whether U of A Conflict of Interest and Commitment Disclosure form must be filed.

I certify that this research will be conducted in accordance with the currently approved protocol/commitments and that no changes to procedures or study documents will be made without the knowledge/approval of IRB.

Signature of Principal Investigator
(required for all projects)

Date

Signature of Departmental Review Chair
(not required for Category C or Category D)

Date

☒ Approve ☐ Disapprove Subject to the following conditions: N/A.		FOR COMMITTEE USE ONLY Period of Approval: JAN 05 2006—DEC 20 2005
Theodore J. Glazewski, Ph.D., Chair Social and Behavioral Sciences Committee		Date Reviewed: JAN 05 2006 ☒ Expedited Review ☐ Full Committee Review	

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