Hands-On Cosmology

Steve Scoville
Brashear High School

Overview:

Less than 100 years ago, there were still scientists, astronomers, and physicists who believed that the universe was only as big as our galaxy and that the positions of the stars were fixed and unchanging. Part of the modern interpretation of the universe includes many features that were not present a century ago, but one of the most fundamental and fundamentally different from previous conceptions of the universe deals with the origin and subsequent expansion of the universe following an event mockingly (at the time) labeled "the Big Bang." The cosmic creation story is a myth that is present in every culture in every language, whereas the Big Bang is a scientific theory. If the Big Bang is to be appreciated as a scientific theory, then the evidence for this conclusion should be presented to students in a manner that is both consistent with scientific practice (and hence based on an evaluation of evidence), as well as comprehensible to a high school student. This unit proposes a series of inquiry-based activities designed to provide or explain the evidence that humans have used to reveal the history of the cosmos, back to its earliest beginnings.

Rationale:

The emphasis of a high school physics course is to instill in the student an appreciation of some of the underlying patterns that humans have discovered concerning the motions and interactions of objects, both large and small, myriad and unitary. Because the very nature of the course is tied to the behavior of tangible, physical objects, physics has been an ideal environment for instruction using inquiry-based techniques. Often, the physical laws that are presented in textbooks will emerge on their own from careful investigations using simple equipment and mathematical tools that are well within the capabilities of the modern high-school student. With the proper guidance, a 17 year old student in a physics classroom in the year 2007 is able to perform similar experiments, make the same sorts of discoveries, and formulate equivalent mathematical relationships that were made by a professional science researcher in a university laboratory 150 years ago. Presented properly, a student gains not only an understanding of the laws of nature, but also an appreciation for the process that leads to the laws' formulation. He or she will come to recognize that $F=ma$ or $KE=1/2\ mv^2$ is not something that humans “made up” the same way that someone “made up” the phrase “And it must follow, as the night the day, thou canst not then be false to any man” or the phrase “They are the egg men. I am the walrus.” In addition to a cognizance of the origins and development of the scientific cannon, educational research has also shown that students who wrestle with uncertainties, discuss their findings and formulate their own models emerge form the experience with a comprehension of the material that is both longer lasting and more readily transferable to novel domains. They remember it, and they can use it.

Certain relationships in nature are not as easily discerned as others. Indeed, it would be a waste of time to force students to independently uncover the secrets of nature that only yielded to some of humanities most brilliant thinkers. One of the benefits of written communication is that once a useful discovery is made or formulation is conceived, then it no longer becomes necessary for every subsequent investigator to re-do the experiment or tread the same intellectual path. There are some physical relationships that will not succumb to investigation without the use of calculus. There are some phenomena that are not observable without expensive or delicate equipment. When teaching students about topics that are thus hidden, it is much more expedient to present to them the findings, without a concurrent opportunity to discover the relationships on their own. The trade-off in this case is that although the course moves much more rapidly through more difficult material, the students are much more likely to view the course content as “what the book says” rather than “what nature has revealed to us.”

The efficacy of an inquiry-based approach to teaching and the difficult nature of complex physical phenomena come into conflict in a particularly interesting way when one approaches the subject of cosmology. How can a teacher provide students the opportunity to work with data that is meaningful to the students and formulate models intended to predict the behavior of objects when the most relevant data is gathered by satellites in space or in underground caverns and the objects under investigation are 1,000 billion billion billion times larger or a trillion trillion times smaller than they are? At these scales and at this level of complexity, intuition that has been developed by playing on a playground or pushing shopping carts in a supermarket is no longer relevant. Common human experience may, in fact, lead a student to formulate models that are exactly opposite what the current science establishment understands about the nature of the universe. Whereas incorrect assumptions and unexpected results are a necessary part of effective inquiry-based learning, students must believe that the data that contradicts their assumption is valid, otherwise it seems a capricious or arbitrary refutation by the teacher. The instructor seems to say simply “your thinking was wrong. It was wrong because I said so.” If the data is incomprehensible, veiled or has a dubious origin, then not only will a student fail to recognize their misconception, but they will also start to doubt the process of the inquiry approach. Their perception of science will change from that of a discipline guided by data-driven hypothesis and revisions to that of a discipline marked by the dominance of the loudest voice or the most powerful proponent of a particular viewpoint. It is obviously the case that, as a human endeavor, the practice of science is colored by those vagaries, however, it is also the goal of every moral scientist to minimize those effects whenever possible – hence peer review of publications, reproduction of experimental results, etc. It is important, then, to make sure that inquiry experiences are structured so that the results of the students' investigations are within their scope of abilities and that the conclusions they are able to draw from their experiences in the classroom build towards scientific concepts that mesh well with existing scientific formulations of the patterns of nature.

High school students are genuinely and immediately engaged by the concepts and implications of physics at the cosmological level. The questions that cosmology proposes to answer are the ones that high school students - indeed virtually every age of human being in every culture since the origins of humanity – inherently find intriguing. How big is space? What are stars? Where did it all come from? What is going to happen to it all? However, the very fact that these questions have been so thoroughly pondered and discussed means that although a high school student may not have heard any other theory or story concerning the relationship between rotational inertia and angular momentum, or the reasons for the increase in electrical resistance in a hot wire, almost all have heard some stories about the origin of the universe. It is vitally important, then, that teachers of cosmology DEMONSTRATE the distinction between the scientific explanation for the existence of stars, galaxies and space from other stories that offer alternative origins. From a student perspective, there will be little difference between an adult telling a story of Chronos and Titans and an adult telling a story of quarks and photons, if neither story is provided with any evidence that demonstrates its validity. In fact, a story that involves feuding personalities or almighty beings will more likely resonate with their prior experience than would a story that relies on a vast soup of hot ions or an infinite region that is growing in size. Here again, the teacher's problem of presenting accessible data and relevant experiences comes to the fore.

What, exactly, must be true for a student to appreciate and gain from experience in the science classroom? Consider the scientific model that the velocity of a wave can be computed by determining its frequency and its wavelength, then multiplying the two quantities together. A teacher could provide students with a few simple tools, such as a stopwatch, ruler, and a small dish of water. Given enough time, high school students could easily work out that $v = f\lambda$, and therefore have faith that such a relationship exists independently of what the teacher says, but simply because that is how nature operates. Note that the skills required to draw such a conclusion (and believe it) are not insignificant. There are many foundational skills that must be in place in order for the relationship to be comprehensible to them: students must be able to use a ruler consistently; they must know how to read the results from a stopwatch; they must know how to compute a velocity, they must know certain definitions (or at least have enough familiarity with the phenomenon so that the question itself is understandable). If any of these pieces are missing, then the classroom experience will not have the anticipated pedagogical outcome – ultimately, students will fail to perceive patterns or order in nature, and they will be "told" the answer by the teacher.

In order to recognize the Big Bang model of the origin of the universe as a hypothesis based on data, students also need to have a repertoire of data gathering and interpretation skills. Because the story that describes the development of the universe is more complex than the story that relates velocity, frequency and wavelength, there are many more intermediate stages that must be established before students can recognize the truth behind the story than with the simpler waves in water. This curricular unit attempts to provide classroom experiences that, along with some math skills and a bit of prior knowledge about light, could build upon each other so that students emerge with an appreciation of cosmology as a set of interconnected stories about objects remote in space and distant in time, yet firmly based on data.

There is a section in the Pittsburgh Public School first year physics curriculum that mandates the teaching of Newton's law of universal gravitation and Kepler's Laws. It is impossible to discuss these topics without arousing student interest, because the discussions inevitably tend towards discussions of the planets of the solar system, moon landings, space travel and the distant stars. It is during these discussions that I frequently get a question that only occasionally comes up at other times during the year: "how do we know that?" This is an incredibly insightful question and, over the years, I have been increasingly dissatisfied with my response to it – particularly when students want to know about the discoveries made in cosmology within the past 50 years. When this question comes up at other times during the year it is a relatively straightforward matter to develop a quick demonstration or lab to convince the students of the validity of a claim (if it ever comes into question). But, as described above, the chain of logic that leads to the stunning conclusions about the distances to stars, the age of the universe, the size of black holes, etc, is so much more complicated and involved that to properly present even the most rudimentary sketch of the chain is often too confusing to be believable. In essence, I end up explaining that we believe A because we believe B because we believe C because... and so on. Unless the chain ends with an obvious and tangible result and C and B and A are all immediately obvious, then my “explanation” has been nothing but confusing – certainly not clear enough to a high school senior that would allow him or her to distinguish it from a fable. My goal for this unit is to give students enough knowledge and experience that they are able to answer, based on what they have seen and done, their own question “how do we know that?” as it applies to certain aspects of cosmology.

How, then, can you lead students to create their own understanding of a situation when they have no contact with, no data on and no instinctive “gut feeling” about the situation under investigation? The resolution to this problem is what makes the study of cosmology useful at the high school level, despite the difficult nature of the observable phenomena: one uses extended analogies. If a suitable analog has been discovered, then students can explore the analogous situation, draw conclusions, recognize patterns and predict behavior about the analogue, which can then be shown to map (with varying degrees of accuracy) onto the cosmological equivalent. In this way students develop along two fronts, they learn about the ideas that form the backbone of modern astronomy, as well as begin to discuss, explicitly, the role of models and analogies in scientific investigations.

While there are a tremendous number of aspects of stars, galaxies and the universe that are well understood by astronomers and cosmologists, there are not necessarily interesting analogs for all of those phenomena. Nor, in fact, do all of those existing analogues necessarily lend themselves to a high school classroom investigation. It is certainly possible to teach students about a subject by showing them videos, reading certain texts, telling them about situations and discussing ideas. However, learning is often accelerated and rendered more robust if these techniques are accompanied by the manipulation of physical objects. The challenge is, then, to identify the core concepts that would be most useful in understanding the reasons for a belief in the Big Bang as the origin of the universe, develop hands-on activities that students could perform in the classroom that could serve as analogues to those core concepts, use the students’ experiences as a springboard for discussion of the actual stellar phenomena. High school physics is traditionally taught with an abundance of labs and activities – most frequently the labs are purified examples of the phenomenon under investigation: if you are studying Newton’s second law you take data on a lab set-up in which forces are applied to masses; if you are investigating the work-kinetic energy theorem, you examine a lab set-up in which work is done on a system and a value for kinetic energy is measured; if lenses are under investigation, then light is passed through lenses and the effects are noted. In all of these examples, the implied message is that the forces, the energy, the light that we measure in the classroom will behave just as force, energy and light behave outside of the classroom. Football players accelerate, cars come screeching to a halt and your contact lenses enable you to see clearly. However, some of the activities in this unit require a further level of abstraction in order to be able to arrive at the desired learning goal. If nuclear binding energy is under consideration it is impossible to “observe” a purified form of the phenomenon in the classroom without resorting to the use of an analogy. Nucleons DO NOT behave just as magnets do when they are brought close together and when you observe magnets closely in the classroom you are NOT seeing protons joining together exactly as you would see outside the classroom (at the core of the sun, for example). But the qualitative nature of the interaction between magnets parallels, under certain circumstances, the behavior of nucleons during fusion reactions. In performing explorations with magnets, students can develop an intuition about the cause of energy release in stars, which helps to answer some of the epistemological questions which form the core of the unit.

I have designed this unit to occupy approximately 3 weeks of my AP mechanics-C physics class. There exists a glorious little 1-month window after AP testing, before the end of the school year, when the AP students, flush from a rigorous year of problem solving and study, giddy with the anticipation of graduation, are unfettered by curricular requirements and the onus of a standardized test. Working with these seniors during these short weeks I hope to implement my unit. Every student in the class has had an introductory year of physics, as well as a second year of physics using calculus techniques to solve problems and performing exacting laboratory experiments. However, as the content of the second year of physics is primarily concerned with linear and rotational motion, energy and momentum, their only exposure to wave phenomena (and light in particular) occurred during their first year in physics. Primarily, I intend to draw on their prior experiences in my first year class, as well as their previous math and chemistry classes.

Objectives:

I would like students to understand why scientists believe in the Big Bang model of the origin of the universe: everything in the observable universe had its origin in an unusual event that took place 13-14 billion years ago, when the entire universe was very small and very hot. They should ask and be able to answer the question “how do we know that?” as it applies to humans’ discovery and development of the core concepts that justify the Big Bang theory. The students responses should reflect more than a rote memorization of the names of discoverers or a description of what their experiment demonstrated; it should be a linked series of arguments that is justifiable by the student at every level because they have personally experienced or, even better, personally uncovered the principles that validate each part of the linked argument.

The content of the unit will connect with 3 of the PA state assessment anchors in an obvious and straightforward manner:
-The concept of the gas laws (S3.4.10.A) must be employed to explain the fact that the universe, though very hot at one point in its life, no longer has such a high temperature.
-The thermal emission of radiation at an early stage of the universe is perceptible today as the cosmic microwave background radiation, and so the concepts of light and light's frequency and wavelength as correlated to the energy it contains (S11.C.2.1.1) must be revisited.
-The entire premise of the unit is that students understand one of the theories explaining the origins of the universe (S11.D.3.1.3)

In addition to the obvious content correlations to the anchors, there are more thematic connections between this unit and the state anchors that are less content-specific. These anchors have more to do with the practice of science, as opposed to the theories or models that emerge from such practice. The activities I propose should satisfy 5 of the anchors as students work though the unit:
-The entire unit was born from my attempt to adequately respond to the question "how do we know that?" It will be made explicit to students at the beginning of the unit that the tasks they will be asked to perform and reflect upon are designed to help them "analyze and explain how to verify the accuracy of scientific facts, principles, theories and laws" (S11.A.1.1.2)
-Because many of the principles involved in the study of cosmology are only accessible to high school students through the use of models or analogies, the unit must therefore satisfy the state requirement that students "analyze or compare the use of both direct and indirect observation as a means to study the world and the universe" (S11.A.1.1.5)
-The way the unit proposes to answer the student's question "how do we know that" relies on data gathering in an inquiry-based manner. As such, it satisfies the 3 anchors related to the interpretation of data: the understanding of experimental limits, the need for internal consistency in any theoretical model, and the need to adequately record and express your findings to others. (S11.A.2.1.3, -4, -5)

Strategies:

In order for effective instruction to take place, the teaching methods must mesh well with the ways in which students learn. Research presented in *How People Learn* (Bransford, et al. 1999) has been correlated to the basic precepts of inquiry practices, and summarized in *Inquiry and the National Science Education Standards, a Guide for Teaching and Learning*. I will explain the ways in which these practices are implemented in my unit for 4 of the 6 research findings described in the *Guide*.

“Research Finding #1: Understanding science is more than knowing facts.” (p.116)

Knowing the interstellar distance to the star Sirius, or naming the most common elements found in the sun, or properly identifying a white dwarf as a stellar remnant are bits of information that some would consider scientific facts about our universe. However, unless placed in a larger context, students will have very little recall of those pieces of knowledge and would most likely lack any ability to make use of the information beyond pure recitation. They would certainly not be able to answer the questions “how do we know: how far away it is?...what it is made of? …where it came from?” A lesson on the Big Bang could easily consist of a reading assignment comprised of 10-20 pages of text, describing the origins of the universe from its infancy at a fraction of a second, through its development of expanding, cooling and coalescing, to its current state. Only by placing the facts in the context of the student’s own experiences will the information become robust enough to allow for easy recall and ready transference. Whenever possible, the unit forces students to uncover data from a particular physical experimental set-up, discuss the significance and reliability of the data, consider the way in which the experiment that they performed acts as an analogy to a similar situation either in an historical scientific investigation (as with parallax, or the Boyle’s law investigation) or as an analogy to an astrophysical process that is currently or has already taken place (as with the heating of a metal coil, expansion on the surface of a balloon, or stretching of light from a “moving” source).

“Research Finding #2: Students build new knowledge and understanding on what they already know and believe” (p.117)

When telling the story of the origin of the universe, one could begin with the moment that it all began – that incomprehensibly hot, dense, small mysterious fraction of a second when everything in the known universe came into existence. However, the problem is that at that instant the universe was INCOMPREHENSIBLY hot, dense, small, etc. If students learn best when material is connected to what they know, then it makes far more sense to begin the story with comfortably familiar concepts, and use those experiences to build towards the singularity that began it all. For this reason, I have arranged the unit around cosmological questions that are often asked by my students, and I have placed them in an order such that the answers will build towards our understanding of the Big Bang.

The questions are all centered around the bright dots that appear in the sky at night. Each question builds on information revealed in the answer provided to the previous question.

1) Where are they?
2) What are they?
3) What are they doing?
4) What were they doing?
5) Where were they?
6) What were they?

The big ideas that should emerge as students go through the unit are that:
1) We can use various techniques to determine the location of bright objects relative to our position here on Earth. These techniques range from the use of simple trigonometric relationships to the use of a relationship between the energy emitted by the object and the energy we actually receive on Earth from that object.

2) There are many sources of light as seen from the surface of the earth. Some are of terrestrial origin, some are large objects that are reflecting light and some are objects or collections of objects much like our sun. We cannot find out the composition of those remote objects by testing them the same way we test rocks from the moon, water from a creek or tumors from a lung because we cannot touch, probe or alter the material itself in any possible way. We must use nothing but the information from light that makes its way to us through space from that remote object. The light that reaches us contains information which can be deciphered by examining the direction, intensity and frequency of the incoming light.

3) Using familiar sonic phenomena (Doppler Shift for waves emitted by a moving source), students should be able to deduce a possible explanation for the apparent shifting of atomic spectra emitted by a distant source as they appear to us on Earth. Students should also be able to create non-sonic physical analogies that correspond to a periodic signal that is emitted by a receding source.

4) If the universe is very large and getting larger, then some time ago it must have been smaller. In fact, if we "rewind" the tape, and imagine the universe in a series of states that recede farther and farther into the past from our own present, then the universe begins to look dramatically different than it does at this moment. The fact that everything currently appears to be rushing away from us in a very particular way indicates that, unless we are at an extraordinarily improbable position, space itself is being created. By measuring the distances between multiple marks on a regularly inflating balloon, students should recognize how Hubble's observations correlate to an expansion of space itself.

5) If space is being created, and the amount of energy remains constant, then temperatures must have been much higher in the early universe. This is

demonstrated by allowing fixed amounts of gasses to heat and cool and measuring the volume at the various temperatures.

6) Matter and light at high temperatures behave in certain ways – atoms cannot form when they are jostled too hard, and unbound charged particles (electrons and protons) will interact with light of any frequency, scattering every possible photon. That behavior resulted in faintly detectable, low frequency light that is pervades the universe today. In this way the Cosmic Background Radiation is considered to be evidence of the big bang as the origin of the universe.

Research Finding #3: Whether and how learners change their ideas depends on what they view as evidence for or against a competing idea. (p.118)

For some students, a science teacher is a source of information; a guide through complex and fascinating intellectual territory; one who reveals truths about the world. To other students a science teacher is a befuddling character, who appears to arbitrarily value some ideas and discount others. The dichotomy emerges when you ask a group of students what happens if you place a piano on an ice rink and give it a push. There are some that will say that the piano will move off at a constant velocity and never stop. These are the students that usually find the most success in a science classroom, primarily because they recognize the nature of the question that is being asked of them, but also because they see how certain details of a situation can be ignored and others must be emphasized. The students that struggle with science are the students who, when asked the question about a shoved piano, will respond that it might go for a little while, but then come to a stop. Doesn't the ice rink have an edge? How did you push the piano, anyway? The underlying principles of motion are blurred by the additional complexity that is inherent in any real-world demonstration (or, for those with good imaginations, thought experiments).

In order to assist students in learning how to eliminate extraneous detail I have structured most of the initial lab experiences as simple challenges. Students are given a specific task to accomplish with specific limitations. In this way my role as arbiter of truth becomes significantly reduced; I can simply defer to the results of an independent check, which are also performed by the students. If I impose certain restrictions on the students' use of materials or access to data (which correspond to the natural limitations scientists encounter when investigating certain phenomena) then their attempts to meet the challenge will often utilize many techniques similar to those used by early scientists. Checking their results is a simple matter of releasing them from the previous limitations and the students naturally discuss the reasons for any discrepancies between their invented techniques and the "obvious" answer. The nature of experimental error naturally arises in the students' discussions of the validity of their findings, because they are forced to compare 2 results, both of which should be, as far as they can tell, correct. Because of this, the differences between the first and second values are much less likely to be ascribed to "human error" or the fact that "we messed up when we did our calculations." The limitations of any experiment are much more obvious to the students when the outcomes of the experiments are not compared to a "correct" value, but rather to a value derived by alternative means. As with all science, cosmological conclusions are based on the data that is gathered from experiments; by independently recognizing the limitations of certain types of experiments, students are able to see the inevitable discrepancy between an idealized scenario and the quirky, aberrant numbers that are the actual results of data collection.

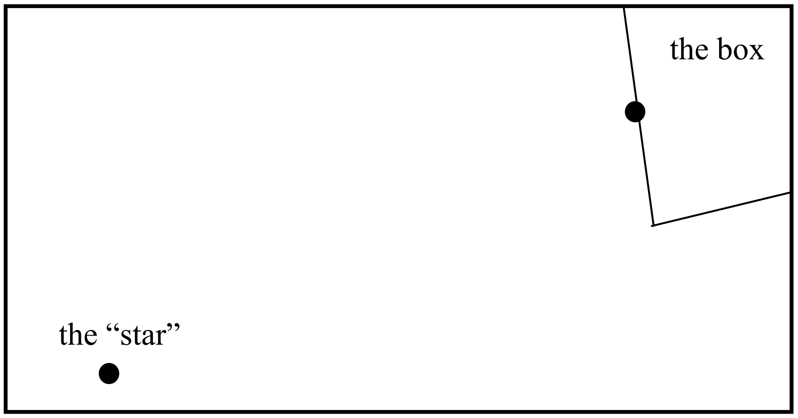
Research finding #4: "Learning is mediated by the social environment in which learners interact with others."

A further benefit of the technique of issuing a simple challenge is that students are forced to pool their knowledge in order to develop and execute a solution method. By focusing the students on the ultimate results of their lab experience, they will become critical of their lab techniques without prompting from the instructor. If there are multiple groups, then any individual student recognizes that if they notice a mistake in their own group's performance, then it is in their best interest to rectify the situation. Students feel compelled to share ideas and react skeptically (within their group) in order to perform better than the other groups involved. The method of ascertaining the "right" answer (relaxing the constraints placed on data collection) validates the efforts of the most effective group, which are then encouraged to share their insights with the rest of the class.

Classroom Activities:

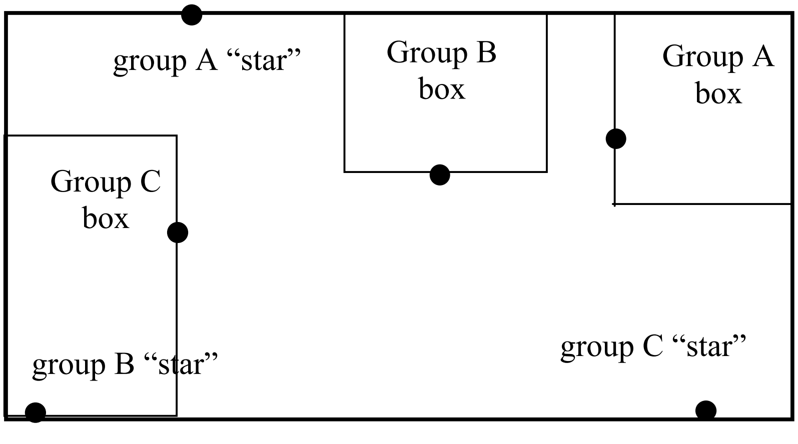
1. Using the PATH of the light beam to determine relative distances

Upon entering the classroom, students are quickly shunted to a small section of the room that has been cordoned off from the rest of the space. This student area, the "box," is delineated by a length of string suspended at roughly waist level that marks the limit of their movement during the experiment. The exact dimensions and orientation of the box with respect to the classroom depend on class size, classroom size and ability level. With a 15m x 9m classroom and 7 students who are comfortable with trigonometric relationships, the box sides are constructed so that they are non-orthogonal to any wall or floor, and restrict the students to a space that is only about 5m x 2m. A dot is placed on the string roughly halfway along one of the longer sides of the box. A second dot (in this case a single bright LED light from an old fish tank) is placed near the ceiling at the other end of the room, roughly 12 m away from the first dot. The lights in the room have been dimmed and the scenario and challenge are issued: find the distance to the "star" (the LED) using only meter sticks, protractors, calculators and string and without ever leaving the box.



Possible arrangement for large room, small class, mathematically able students

Variations to accommodate different physical set-ups, class sizes and ability levels could include taking the activity into a hallway, creation of multiple boxes at different corners of the room, or making the box sides perpendicular to easily identifiable reference lines, like walls or floor tiles, etc. Whatever modifications take place, it is important that the some characteristics be maintained. Students should not be allowed to leave the box, but the confinement should not be so restrictive that they are not able to make geometrical constructions with the meter sticks inside the box. The "star" should be clearly visible, but not close to other room reference points with easily measured characteristics, like ceiling tiles, floor tiles or wall panels.



Possible arrangement for smaller room, large class, students with less trig exposure

If the students are familiar with the use of right triangles to solve for particular lengths, then they will look to the structure of the room for right angles. With careful structure and placement of the box and star, however, no easy triangles will be apparent. One possible solution method students may use to determine the distance between their own dot and that of the star will be to construct a right angle in their box with the hypotenuse of the right triangle as the unknown distance. Students familiar with the Law of Sines may simply use the string that forms the box as a leg of a triangle and measure the 2 angles they can easily access. In both cases it will be important for them to measure both an accurate length within their confined box area as well as 2 accurate angle measurements.

The intention is to force students to treat the location of the star as an arbitrary point, lacking any intermediate reference except for that which they construct within the box. After the activity is performed, students should recognize the reasons for the placement and nature of the "star" and the role of the box. Students should be asked to consider the ways in which the classroom activity mimics the limitations and abilities of both ancient and modern astronomers. Students should recognize that the LED is meant to represent a distant star and that the reason why the students were confined to the box was that astronomers, for the most part, are stuck here on the earth.

When discussing the activity, there are some questions that, if not raised by the students, should be raised by the teacher:
- what was the reason why didn't your distance measurements come out exactly "right?" (i.e., match the measurements that were obtained using a tape measure, for example). Here students should recognize the limitations of the protractor for measuring angles and the correlation between the accuracy of the baseline triangle measurement with the overall distance measurement. If asked what the largest baseline measurement humans can achieve, most will respond that it must be a distance that is limited by the curvature of the earth – the sides of the baseline must be able to see each other when they look out to the distant star; a distance of a few hundred kilometers. If pressed on the point (by asking, for example, if it was necessary that the angle measurements be made at the same time), students should come to see that the biggest baseline is actually the distance from one edge of earth's orbit to the other – a distance approximately 6 orders of magnitude larger than their first guess.

-What assumptions did the students have to make that enabled them to use the laws of trigonometry to solve the problem? This will be a puzzling problem to the students, because the assumptions are so deeply ingrained that most people are blind to their existence. The first assumption is that the light beams from the star comprise the legs of the triangle and the second assumption is that light travels through space in straight lines. While both assumptions certainly hold true for the experiment as performed in the classroom, it will be useful to make the assumptions explicit early in the unit, so that when they arise again (as when discussing the curvature of spacetime) students will see why it is imperative that the assumptions made in an experiment are understood by the experimenters.

- The teacher may also wish to explore with the students some of the ways in which actual parallax measurements are made as opposed to the distance measurements made in the classroom. The main difference is that astronomers look for the motion of nearby stars with respect to the "background stars" that is caused when the points are viewed from a slightly different perspective instead of looking at the change in viewing angle with respect to an arbitrary baseline. It should be emphasized, however, that in either case, parallax or classroom, the significant information was the DIRECTION from which the light reached the observer.

- Actual astronomical observations can yield angle measurements that are on the order of 4 milliarcseconds. In conjunction with the baseline of the diameter of the earth's orbit, this can give distance measurements accurate to within 10% out to approximately 100 light years.

2. Using the INTENSITY of the light to determine relative distances

Although an effective means of determining the locations of stars within a certain radius of the Earth, there are many stars for which a parallax measurement does not yield any useful data. According to our best instrumentation and data concerning angular shifts, the object might as well be infinitely far away. How, then do we find out about the locations of stars or other remote objects that lie beyond the parallax method of judging distances? As a class, students should recognize that the important information that they gleaned from their classroom and outdoor experience was the fact that light came from a particular direction. Students should recognize that the assumption that they made that enabled them to construct triangles was that light travels in a straight line. While this was never stated explicitly during our investigation, it should be pointed out now, for 2 reasons. Firstly, this assumption will be addressed later in the unit when the nature of light paths traversing a curved 3-D space begins to challenge our intuition about straight lines and therefore students should be aware of how deeply and innately this assumption guides our understanding of our limited experience here on Earth. Secondly, once this assumption is addressed, it should make the students aware of the fact that light carries much more information than simply its direction. Even students who have not had extensive exposure to optics or the EM spectrum should recognize that the intensity of the light gives some clues as to the location of the source. Even before experimentation begins, students should be able to infer an inverse relationship between distance and intensity, although the exact nature of the relationship may not be immediately obvious. Students are then challenged to determine the exact nature of the inverse relationship (logarithmic? exponential? something more sinister?) by using any CBL (Calculator Based Laboratory) or other photometric equipment. In cases where the class size is small, a single frosted glass bulb can be used as a light source and students can array themselves around the object to take measurements ranging from a distance of 1 cm to 50 cm or more. It will be important to limit the input to the photometer devices (an index card wrapped in a cylinder and placed at the probe end of the photometer should provide some degree of directional precision) to ensure that student groups do not disturb the readings for other groups by standing behind the bulbs and reflecting additional light into their apparatus. There may be small but measurable fluctuations in the intensity of the bulb due to the interaction between the thermal and resistive properties of the filament. An average value taken over the period of many cycles of fluctuation at a given distance, however, give results that can be used to show the inverse square law. Students should use their calculators to determine a regression formula that most nearly corresponds to the data. This can then be achieved by first looking at an obviously incorrect formula – a simple linear relationship – and looking at the correlation coefficient.

Once students have proposed relationships and agree on the best fitting relationship, they should attempt, if possible, to give some reason for the validity of this relationship. Why should the intensity of the light diminish as the distance squared? Why not as the distance cubed or halved, etc? It may be useful to recall the definition of intensity as it relates to the flow of energy through a given area in a certain amount of time. Students should then be asked to consider, instead of a continual source, a single pulse of light energy as it expands outwards in a sphere. If needed, a graph of the surface area of the sphere as it relates to radius can be sketched or computed and students should recognize that the same energy is spread over an area that increases as the square of the distance, hence decreasing the intensity by a similar factor. How then does this useful fact enable us to determine the distances to remote stars?

The bulb that had been in use to generate the intensity data for the graphs is then placed at one end of the classroom and the students, armed with their photometers, are placed at a distance of 2-3 m away. Again, students must use their data to compute the distance to the remote object based only on the light emanating from the object. Because all of their previous data was gathered from the same source, there should be no need, at this point, to know the absolute intensity of the source.

Once the measurements are made, and estimates of distances are given, students can measure the distance using more traditional methods. Again, a discussion should follow that addresses the following questions: how is this like what astronomers do/did? How is this unlike what astronomers do/did? What were the limitations to the accuracy of the distance measurements? What information did you need to have in order to successfully judge distances to light sources? The last question is the one that leads to the next link in the conceptual chain: in order to know the distance to the object, one must know one of 2 important bits of data: the actual distance to objects that have a measured intensity as seen from Earth, or the absolute intensity of the objects.

As the students look on, move the light source even farther from them, then change the light bulb to one of a higher intensity. Ask them if they could compute the distance from their photometer to the bulb at this point. There should be a variety of responses, some proposing that this experiment will be no different than what they had done previously and some proposing that there is something missing. As an analogy, draw a stick figure on the board and ask if this is a small person up close, or a large person far away? Is there any way to tell, at this moment? If you were fortunate enough to see the man fall over, could you then use that additional information to find out whether it was a large man or a small man? A slowly falling man would imply a large person seen from afar, whereas a quickly toppling man must appear a given size due to increased proximity. In other words, if we could find out something about the remote object (man or star) that would give us a clue about its absolute magnitude (height or intensity) that was independent from its apparent magnitude, we could then extend our cosmic measurements to as far out as we can measure the apparent magnitude (height or intensity) of those remote objects.

Students are then given 2 words: “Leavitt” and “Cepheid” and must use the internet to determine how astronomers solved the problem that faces them in the classroom. There are numerous sources which will tell the story of the Harvard employee who, because of her gender and the social mores of the times, was unable to utilize her intellectual capacity to its fullest extent, yet managed to find the very correlation needed that enabled astronomers to assess distances out 100,000 times farther than before.

Interestingly, the periodic fluctuations perceived in the light bulbs due to the temperature increase of the filament, increased resistivity and consequent decrease in luminosity and temperature, are wonderful analogies to methods used by early astronomers for finding the absolute magnitude of the Cepheid variables.

Students must recognize that in order to be viable distance indicator, at least one Cepheid variable must lie within the range of parallax measurements. However, once that distance is established, then one can see how the distance ladder is established – one measurement giving a basis for an even larger measurement. Once the calibration is complete, then any Cepheid, no matter how dim, can be used to measure distances. It is with this information that Hubble discovered that the objects in the sky that appeared extremely small and dim only appeared that way because they were fantastically far away. Hubble's recognition of the significance of the Cepheid variable data confirmed that there are many, many galaxies in the universe and that the Milky Way is just one of a myriad of "island universes."

3. Using the FREQUENCIES of the light beam to determine relative distances.

If all stars shone with the same intensity, then it would be relatively easy to determine their distances from us. The distance to a nearby star – the sun, for example – could be ascertained via a parallax measurement and then the star's intensity at a known distance could be used to calibrate the curve for the diminishing apparent brightness as seen from the Earth. Unfortunately, throbbing Cepheid variables and stars exactly like our Sun are not the only 2 types of stars in the sky. If all of the billions of stars have random intensities, then the hope of using their apparent brightness to gauge distance is futile. Fortunately, the light that we receive from those distant fires carries more information than simply its direction of origin and its strength upon arrival.

Students should have enough background information from previous physics classes to recall that colors of objects exist because EM waves of a particular frequency are impinging on their eyes. Small slides containing diffraction gratings can be used to demonstrate the spectral difference between fluorescent and incandescent lights. Ask the students if this could, potentially, be used to find the distance between the Earth and the light source itself. Much as with the Cepheid variables, it should be apparent that if there were some aspect of the light that gave some hint as to its intensity when it was emitted, then the perceived intensity would allow for a simple calculation of distance. This can be accomplished by using two different wattage incandescent and florescent bulbs, so that one has an obviously larger intrinsic brightness. Students are then asked to assume that all bulbs follow this pattern of brightness – where luminosity corresponds to the types of frequencies present, and asked to use the information to determine which "star" is farther away if one appears brighter or dimmer than the other. Since the stars are not, in fact, light bulbs, the system of correlating frequencies to intensities will only work if it is the case that there is some relationship between the 2 quantities.

Shut off the overhead lights so that the room becomes dark. Place a heating coil at the front of the room. This can be a ceramic and wire device as might be used in a hair dryer or old beverage warmer or a table-top cooking element. Students are to describe what frequencies they are receiving from the item on the table top. If the room is sufficiently dark, then the response should be "none" –

which can be clarified to be “none, in the visible range.” The heating element is then turned on and allowed to warm up. If the temperature is variable, then begin at a low setting, so that the metal is just barely glowing in the visible range. Ask again for the frequencies present. Students can, again, use the diffraction gratings to analyze the precise frequencies present. Continue to increase the temperature of the radiating object and note the changes that are perceived as a whole by the naked eye as well as in parts with the help of the diffraction grating. Students should notice not only a change in the frequencies present, but they should also notice that the light appears to get brighter as the temperature is increased. Here, then, is the correlation that we have been looking for: if there are hotter stars, then they will have different emission spectra and also have a different intensity.

These 3 methods of distance calculation, which utilize the direction of the incoming light, the intensity of the incoming light and the frequency of the incoming light, comprise the first few rungs of the cosmic distance ladder. Each method has limitations and an inherent error associated with it. However, this set of data enables astronomers to plot the positions of millions upon millions of stars, some of which are millions of light years distant from the Earth. This analysis of stellar distance provides the conceptual framework for the analysis of phenomena later in the unit. The universe beyond our solar system is only accessible to humans via the light that we receive from afar. Whatever processes take place in those remote locations will only be known by our analysis of the products that are spewed forth into space and absorbed by the detectors on our home world. However, by putting together our understanding of how materials behave here on Earth with the evidence we have gleaned from the universe beyond, we have been able to assemble a story that extends out 13 billion light years into space and 13 billion years back in time.

Annotated Bibliography/Resources:

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<http://www.pbs.org/wgbh/aso/databank/entries/dp12le.html>

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9/24/1998, University of California, Riverside
<http://physics.ucr.edu/~wudka/Physics7/Notes_www/node109.html>

“Interactive HR Diagrams”, University of Utah, 2003 <http://aspire.cosmic-ray.org/labs/star_life/hr_interactive.html>

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<http://www.colorado.edu/physics/2000/quantumzone/index.html>

Charap, JM. Explaining the Universe. Princeton, Princeton University Press, 2002.
(primarily pages 24-42)
This segment of the text includes a very brief recap of 20th century astronomical advancements, absorption spectra, the relationship between the mass of a star and its eventual fate, the use of standard candles, the Hubble expansion and its relationship to the Cosmological Constant

Cole, K.C. The Hole in the Universe. New York, Harcourt, Inc., 2001.
(primarily pages 128-135)
This portion of the book explains the curvature of space-time due to the presence of a mass and the implications for the fate of the universe

Hawking, Stephen. A Brief History of Time. Toronto, Bantam Books, 1988.
(primarily pages 35-50)
This section of the book describes Hubble's discovery linking the recessional velocities of galaxies and their distances, and raises the question of a closed vs. open universe.

Reese, Martin. Just Six Numbers. New York, Basic Books, 2000.
(primarily pages 45-74)
This section of the book discusses fusion reactions in stars and the energy released as light and the implications for the expansion of the universe

Serway, Raymond A. and Faughn, Jerry S. College Physics. Pacific Grove, CA. Thomson, 1999
A college-level physics textbook which contains information about the Electromagnetic spectrum, some color photos of sample emission and absorption spectra, sample problems for $E=mc^2$ and particle binding and values for particle rest-masses.

NRC, Inquiry and the National Science Education Standards, A Guide for Teaching and Learning. Washington, D.C., National Academy Press, 2000.
A summary of the philosophy, methods of practice and benefits of using inquiry-based methodology to design and execute curriculum.

Appendix:

Pennsyvania Department Of Education Assessment Anchors And Eligible Content Addressed:

(S11.C.1.1.5) Predict the behavior of gases through the application of laws (ie., Boyle's law, Charles' law or ideal gas law).
(S11.C.2.1.1) Compare or analyze different types f waves in the electromagnetic spectrum (eg. ultraviolet, infrared, visible light, x-rays, microwaves) as it relaters to their properties, energy levels, and motion.
(S11.D.3.1.3) Explain the current scientific theories of the origin of the solar system and universe big bang theory, solar nebular theory, stellar evolution).
(S11.A.1.1.2) Analyze and explain how to verify the accuracy of scientific facts, principles, theories and laws.
(S11.A.1.1.5) Analyze or compare the use of both direct and indirect observation as means to study the world and the universe (eg. the behavior of atoms, function of cells, birth of stars)
(S11.A.2.1.3) Use data to make inferences and predictions, or to draw conclusions, demonstrating understanding of experimental limits
(S11.A.2.1.4) Critique the results and conclusions of scientific inquiry for consistency and logic
(S11.A.2.1.5) Communicate results of investigations using multiple representations

Pennsylvania State Standards For Science And Technology Addressed:

(3.4.10.A) Explain concepts about the structure and properties of matter.
Predict the behavior of gases through the use of Boyle's, Charles' or the ideal gas law, in everyday situations
(3.4.12.D) Analyze the essential ideas about the composition and structure of the universe.
Analyze the Big Bang Theory's use of gravitation and nuclear reaction to explain a possible origin of the universe.
Compare the use of visual, radio and x-ray telescopes to collect data regarding the structure and evolution of the universe.
(3.4.10.A) Essential ideas about the composition and structure of the universe.

- Compare the basic structures of the universe (e.g., galaxy types, nova, black holes, neutron stars).
- Describe the nuclear processes involved in energy production in a star.
- Explain the "red-shift" and Hubble's use of it to determine stellar distance and movement.

- Compare absolute versus apparent star magnitude and their relation to stellar distance.
- Identify and analyze the findings of several space instruments in regard to the extent and composition of the solar system and universe.

(3.2.12.C.) Apply the elements of scientific inquiry to solve multi-step problems.

- Generate questions about objects, organisms and/or events that can be answered through scientific investigations.
- Evaluate the appropriateness of questions.
- Design an investigation with adequate control and limited variables to investigate a question.
- Organize experimental information using analytic and descriptive techniques.
- Evaluate the significance of experimental information in answering the question.
- Project additional questions from a research study that could be studied.