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Biography of a Star: Our Sun's Birth, Life, and Death

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They are born. They take shape. They go through a turbulent youth, and then they live out their lives in a predictable pattern. Maybe they have companions they provide for. Someday they rapidly decline and die. Stars, in many ways, are just like people.

Our Sun, constant and permanent though it may seem, is no exception. Once, people regarded the Sun as a different sort of object than the stars. It ruled the day; stars adorned the night. But over the past few centuries astronomers have come to recognize that the Sun is just one middle-aged member of the vast family of stars. From far away, the Sun would look just like any other star -- a point of light. And like any other star, the Sun is mortal.

The realization that the Sun is a star has done wonders for astronomy. By studying the Sun, the closest star, scientists have learned about all stars. Conversely, by studying the stars, in all their variety, scientists have learned about the past and future of the Sun. This, in turn, has told them about the past and future of life on Earth. After all, the Sun is the ultimate root of our food chain. When the Sun came into being, it provided the light and warmth needed to make Earth a hospitable place. When it dies, our planet will no longer be fit for living things.

Despite the progress of astronomy over the past centuries, our knowledge of stars is by no means complete. Recent advances in astronomy, ranging from instruments capable of observing 100 stars at once to the Keck telescope with its enormous mirror 10 meters (33 feet) across (compared to Hubble Space Telescope's 2.4 meters), have joined forces with powerful new computers to propel our understanding of how stars are born, evolve, and die.

Stayin' Alive

The importance of the Sun to Earth is one of the main reasons scientists want to understand it. In fact, the impetus for solar science early this century came not from astronomers, but from geologists. Using radioactive-isotope dating at the beginning of this century, geologists determined that the oldest rocks on Earth are about 4 billion years old. (More recently, rocks brought back from the Moon, as well as the now-famous Mars meteorite, show that this is a common age for planets in the solar system.) Assuming that Earth and the other planets formed around the same time as the Sun, these rock ages indicate that the Sun came into being 4.5 to 5 billion years ago.

The extreme age came as a surprise to most scientists. Astronomers already knew the basic facts about the Sun. It is simply a huge ball of gas, mostly hydrogen, held together by its own powerful gravity; it gives off light because of some source of energy within it. Astronomers thought that this source of energy was a slow but steady contraction of the Sun under the force of gravity, much as a house slowly settles. But this source of energy would only have kept the Sun alive for 20 million years. Other sources of energy -- say, a huge fire -- would burn out even quicker.


The womb. The Orion nebula, long a favorite of backyard observers, is the tip of a huge cloud of gas and dust floating in interstellar space. Within the cloud are dense lumps where stars are sired. Photo courtesy of Lick Observatory.

The solution to this age discrepancy is an example of how leaps in scientific understanding frequently involve the insights from disparate fields of study. In the years after World War I, British astronomer Arthur Eddington put together three ideas and boldly proposed a new energy source for the Sun.

First, astronomers knew that the Sun has to be extremely hot and dense in its center if it is to support its own weight. Gas at a high temperature exerts a strong pressure, and this holds up the outer layers of the Sun. Second, physicists had recently compared the weight of four atoms of hydrogen with that of one helium atom. Both the hydrogen quadruplet and the helium are composed of essentially the same number of subatomic particles. Yet the helium weighs less. Third, Albert Einstein's new theory of relativity showed that matter can be converted into energy (E=mc2).

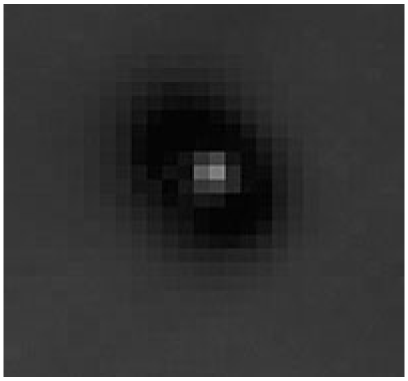
At first glance, these three ideas might seem totally unrelated. But from them, Eddington deduced that the Sun's energy source was a process then unknown on Earth: the nuclear fusion of hydrogen to helium.

The word nuclear has gotten a bad rap. Normally people utter it in the same breath as mass death. But in happier circumstances, nuclear processes are responsible for maintaining all life on Earth. Deep in the hot and dense core of the Sun, hydrogen atoms are squeezed together, or fused, into helium atoms -- roughly akin to crunching a few baseballs together and getting a football. A helium atom has less mass than the hydrogen atoms from which it was created, and this missing mass turns into energy.

Few other schemes can generate as much energy as nuclear fusion. A small amount of hydrogen can produce an immense amount of energy -- which is why nuclear bombs are so destructive, and why the Sun can keeping going for billions of years.

Family History

How did the Sun become hot and dense to begin with? This is the secret of stellar birth. Though we weren't around to witness the birth of our provider, we can read its early life history in the stars. Specifically, we can look out into space and see new stars being born right now.


The baby. Swaddled in a disc of dust and gas not much larger than our solar system, this newborn star is a recent addition to the Orion family. The proud parents have the Hubble Space Telescope to thank for the portrait. Photo courtesy of Chris O’Dell of Rice University and NASA.

The closest example is in the Orion constellation, a pattern of bright stars easily visible from the Northern Hemisphere in winter. For thousands of years, the pattern has reminded many viewers of a person with one raised arm, wearing a belt. If you look below the belt, there are four bright, blue stars called the Trapezium. If you look even more closely with binoculars, a fuzzy patch called the Orion nebula becomes visible.

This is a stellar nursery -- an enormous, lumpy cloud of cold gas and dust which is turning into hundreds of new stars. The gas is mostly hydrogen; the dust is something like the dust in a desert storm: basically, microscopic rocks. Within the clouds are hundreds of condensed, cold lumps of gas and dust. A disturbance, such as a blast wave from a nearby stellar explosion, can cause each lump to begin collapsing under its own weight.

We can see many examples of such star-forming regions. It seems that stars, like people, are born in families. For stars, these very large families are called clusters, and we know of

1,500 such clusters. Astronomers presume that the Sun was also born into a family, but, as seems to be typical of clusters, the Sun's probably broke up in the first 100 million years of its life. About two-thirds of stars are actually born with nearby twins or triplets, but the Sun is alone.

Astronomers aren't in complete agreement on where the clouds themselves come from, but it's likely that the gas and dust have more than one source. There is the pristine hydrogen gas synthesized in the creation of the universe [see "The Biggest Bang of Them All," The Universe in the Classroom, first quarter 1997]. There is the gas and dust that our galaxy has pilfered from its satellite galaxies, such as the "Magellanic stream," a streamer of gas ripped out of the nearby Large Magellanic Cloud. And there is the gas and dust from previous generations of stars. When stars die, they blow much of their material back into space, where it can form other stars. Stars in the Galaxy are the ultimate recycling machines: They use gas and dust over and over again.

When the massive lump of cold dust and gas which became our Sun collapsed, the nuclear forces began to come into play. The weight of all that dust and gas produced great pressure and density at the center, and the friction of the infalling particles released heat. When the temperature in the core reached several million degrees, the hydrogen atoms started to fuse together, forming helium atoms. This released energy, the pressure increased, more atoms fused together, more energy was released, and so on, and so on. A chain reaction started that will go on for billions of years.

The outward pressure created by this nuclear fusion counterbalanced the inward pressure of gravity, and when the two canceled each other out, the natal lump of dust and gas stopped collapsing. Astronomers think this process took about 100 million years. The Sun was born.

Although the embryonic Sun slurped up most of the gas and dust from the lump, some crumbs were left over. As this extra material spun around the center, the centrifugal force prevented it from falling into the center. Instead, it flattened into a whirling disc. Astronomers have seen such discs around many young stars. Within these discs, scientists think that blobs of material clump together into the smallish bodies we call planets, asteroids, and comets.

The sisters. The Pleiades star cluster contains 200 stars, all born 50 or so million years ago. The wisps of dust around the stars might be remnants of the cloud from which the bicenttuplets emerged. Photo courtesy of Mount Wilson Observatory.

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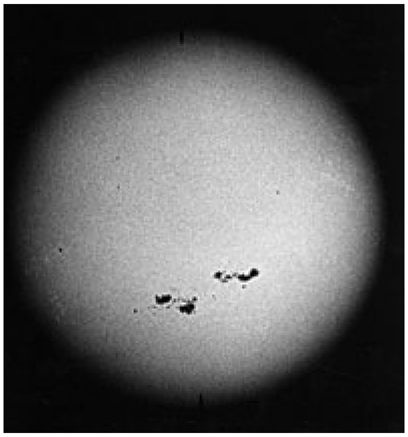
Just Right

Depending on the size of the original lump of gas and dust, the process of stellar birth can give rise to different sorts of stars. A small lump never develops high enough pressures and temperatures to start nuclear fusion. It is doomed to remain a dark, dismal stellar wanna-be -- a so-called brown dwarf. A larger lump becomes a large star, so hot and bright that it burns itself out in a few tens of millions of years. A lump in the middle, not too small and not too large, becomes a middling star such as the Sun. Which is good: If the Sun had been much smaller, Earth would have been a dark, dead world; much larger, and Earth would have been broiled.

In its early years, the Sun went through a tempestuous youth, whipping up strong winds that cleared the solar system of whatever gas had not been incorporated into a planet. But then the Sun settled down. From studying rocks, fossils, and Antarctic ice, scientists think the Sun has been brightening over time, but only slightly.

And how much longer will it continue to shine? For an idea of the Sun's life expectancy, astronomers look to clusters of stars, such as one named Messier 67, which is about the same age as our Sun. By simulating the life cycles of these stars on a computer, astronomers have ascertained how long stars live. They predict that the Sun will be able to fuse hydrogen into helium in its core at about the same rate for another 5 billion years. (What a relief!) If the Sun were a car, the gas tank would now be half full.



The middle-aged suburbanite. The Sun is a two-car-garage kind of star. Its stability and temperance make it an ideal provider for tender planets. Photo courtesy of Mount Wilson Observatory.

What will happen when the Sun does run out of gas? (Hydrogen gas, that is.) Fortunately, the Sun will still have reserves of hydrogen in the layers that surround the core. The core will heat up this shell of hydrogen. When the shell gets hot enough to fuse hydrogen to helium, the release of energy will carry on there. It is as if the driver of the car poured an extra few gallons into the fuel tank.

But this trick has a price. The source of energy will no longer be the dense, massive core, but rather a shell closer to the surface -- and that will make a big (so to speak) difference in the structure of the Sun. The Sun will puff up until its radius is 30 times greater. It will become a red giant, similar to the star Arcturus, though much smaller than a supergiant such as Betelgeuse (see photo on p. 3). A red giant is red because its exterior cooled from 9,000 to 3,000 degrees Fahrenheit as it expanded; for a star, red means cool. This red-giant stage will last for about 2 billion years.

That Time Bomb in the Middle

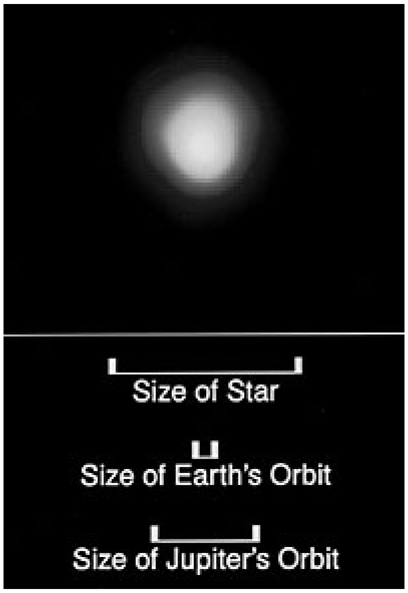
The striking but now-outdated video Universe, produced by NASA in the 1970s, shows the red-giant Sun engulfing the Earth. Though certainly dramatic, this is now thought to be incorrect. Astronomers have had to scale down their estimates of the size of red giants based on data from the satellite Hipparcos and from the new optical and infrared interferometers -- networks of telescopes which can take images of large, nearby stars. Now we think the Sun will not engulf us when it becomes a red giant.

But that is small comfort. In its retirement from normal core fusion, our previously nurturing star will care little for its planetary children. It will be pumping out a thousand times more energy, making Earth a good approximation to hell. To add insult to injury, the solar wind -- a stream of particles which now gives us fun things such as the aurora borealis -- will become a cyclone that will make radio communication impossible and perhaps evaporate the atmosphere altogether. Looking on the bright side, the red-giant Sun may be warm enough to melt the water-rich but now-frozen moons of Jupiter and Saturn. Humanity, if it is still around, might relocate there.

Meanwhile, what happens to all that helium being produced in the shell? It gently rains onto the dead, but still toasty, core of the Sun, making the core more massive and more compressed. This raises the temperature of the core until suddenly -- and I really do mean suddenly, as in seconds -- the helium in the core fires up and begins to fuse itself into carbon. Using the fuel-tank analogy, this is as if the exhaust itself starts to burn.

The end is drawing near. Now the Sun has to rearrange its internal structure all over again, as its source of energy is once again the central core. The Sun will contract back to a bit larger than its original radius and will give off 10 times as much energy as what we are used to now. This phase only lasts another 500 million years, as there are a lot fewer helium nuclei (it took four hydrogen nuclei to make one helium nucleus, and three heliums to make one carbon) and the energy production is much less efficient.

As the Sun exhausts the helium in the core, it desperately staves off the inevitable by resorting again to those reserves in its outer layers. Again the Sun expands. This time, it grows so large that its outer edge is only weakly gravitationally bound to the core. The Sun barely holds itself together anymore. This eleventh-hour attempt at life-support is pitifully ineffective; the final red-giant stage can be maintained for only 100 million years.



The last fling. Its normal life over, Betelgeuse is now a red supergiant — red, because its surface is a comparatively cool red-hot, and supergiant, because it is hundreds of times larger than the Sun and ten times more massive. Its waistline, however, is not a sign of might, but of impending death. Photo courtesy of Andrea Dupree, Ronald Gilliland, NASA, and the European Space Agency.

At this point, things will really start falling apart. The Sun's outer layers, freed from the gravitational clutches of the core, will waft away. Over the course of about 10,000 years, these layers will spread out into space as an enormous sphere of gas lit up by the now-naked hot core. These layers constitute a "planetary nebula," so called because in a small telescope the gas cloud looks a bit like the disc of a planet (see photo on p. 3). The hot core is now a "white dwarf," a stellar cinder. As a white dwarf, the ex-Sun will glow white-hot for a near-eternity.

Alas, there will be no dramatic explosions to entertain our distant descendants: The Sun would have had to start with at least eight times more mass to die the spectacular death of a supernova. The Sun, modest in life, is subdued in death. After the planetary nebula fades, there is no nuclear fusion at all (no extra fuel, no fuel tank, not even the trunk is left), just a lump of hot carbon and some happy memories. The Sun will be well and truly dead.

The sphere of gas drifts off and eventually is gathered up in a new cloud, and become part of the next generation of star formation. Perhaps one day, the ashes of the Sun will throw their lot in with another star to be born, live, die, and, perhaps, give sustenance to other warm little planets.

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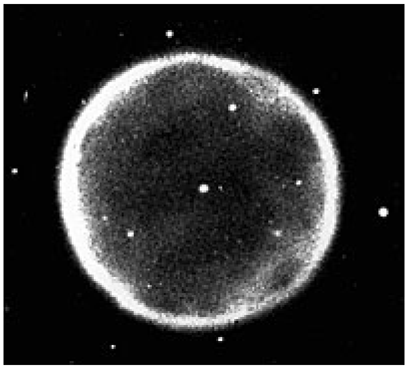

The cremation. After stars like the Sun fuse their last atom, they scatter their ashes into space as a so-called planetary nebula, such as Abell 39. At the center of the nebula is what’s left of the star: a slowly decaying “white dwarf.” Photo courtesy of George Jacoby of the National Optical Astronomy Observatories.

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Classroom Activity: Pinhole Protractor

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For objects just around us, out to about 50 feet, we perceive distances with our binocular vision. The brain compares the two views of our eyes and estimates distances from the differences between the two. You can see these two views by holding your finger in front of your face and closing each eye in turn. Because each eye has a slightly different view, your finger appears to jump back and forth.

But for more distant objects, our binocular vision becomes inaccurate, because the two views are nearly identical. We cannot directly perceive the distances or sizes of far-away objects. Instead, our eyes only detect the angular size of objects. In other words, we cannot estimate the physical size of an object (in feet or meters), but only the angle it covers (in degrees). If an object is familiar to you -- that is, you know its actual physical size -- your brain can use this knowledge and the object's angular size to estimate its distance. But if you don't know its physical size, you cannot estimate the distance.

Suppose you see a UFO in the sky. Since you don't know much about UFOs, you can't estimate its distance. It could be a small object close up or a large object far away. This is one reason that astronomers tend to distrust UFO reports. People have reported seeing a saucer hovering over a nearby building when in fact it was a blimp many miles away. But if you are able to see something you recognize -- say, your friend waving to you from the blimp gondola -- you can estimate the distance more easily. Based on your friend's apparent angular size and your knowledge of his actual size, you can estimate his distance. Astronomers use a similar process to determine distances of stars and galaxies.

In principle, you could measure angular size with the same device normally used in the classroom to measure angles: a protractor. Imagine if you put a protractor next to your face, with its center at one of your eyes. To measure the angle between the two sides of an object, you would turn your head until the zero-degree mark pointed in the direction of one side of the object. Then, you would read off the angle of the direction to the other side. With an actual protractor, however, this technique takes two people -- the numbers and divisions are too difficult for one person to see.

A pinhole protractor solves this problem in a convenient, inexpensive way. Traditionally, astronomy teachers have used a cross staff to measure angles and explore parallax. But the pinhole protractor is cheaper, easier, and more compact. All it takes is a sheet of card stock and the photocopy-ready pattern on p. 7. Each student can make an instrument. When we have tested the device in our classrooms, we have found that students grasp the concepts of angular size and parallax more easily than when they used the cross staff.

Objectives

In Part I of this activity, students will make a pinhole protractor. They will use it to measure angles and calculate distances in an everyday situation. In so doing, they will see how astronomers use similar measurements and calculations to study the universe.

In Part II, which will appear in a future issue of The Universe in the Classroom, students will see how astronomers use parallax -- an extension of binocular vision -- to determine the distances of stars in the Sun's neighborhood. Parts I and II can be done separately.

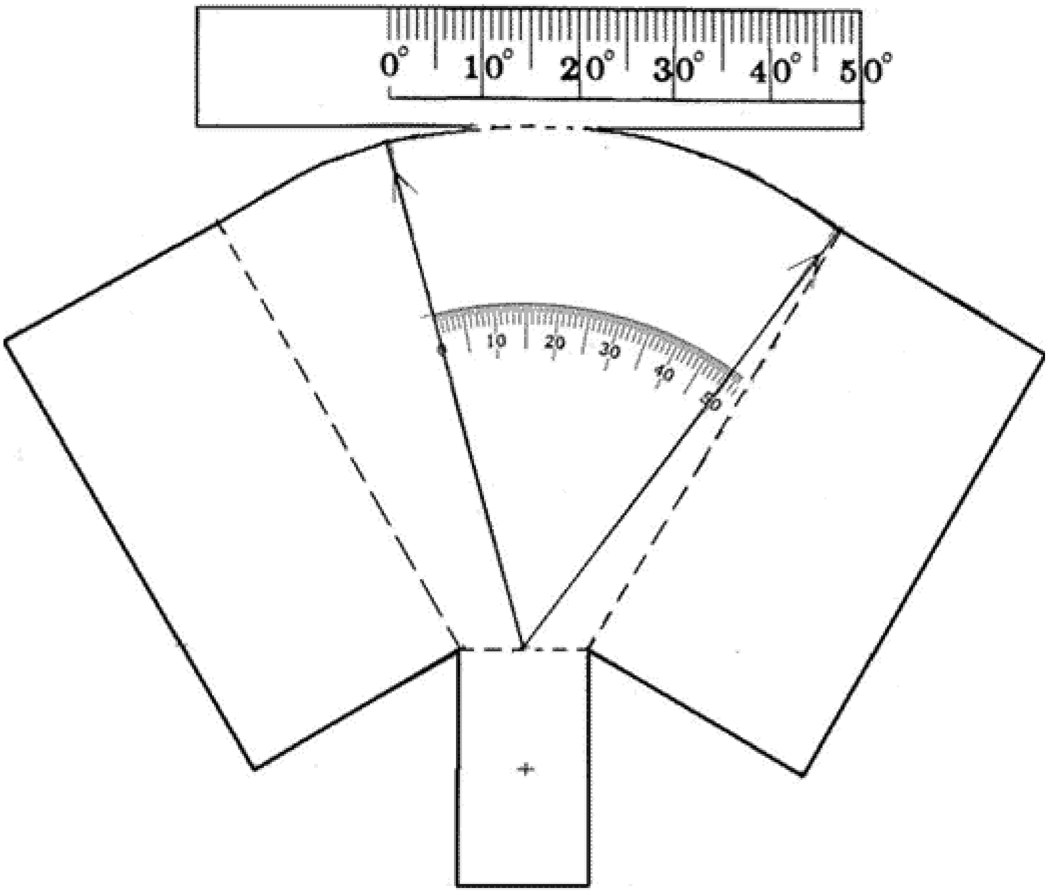
Constructing and Using the Pinhole Protractor

Materials

- thin cardboard, manila file folder, or other stiff paper
- photocopies of the pinhole-protractor pattern (below)
- transparent tape
- a calculator
- a tape measure, meter stick, or yard stick
- a roll of masking tape

Constructing the Protractor

- Glue or paste the pattern onto the manila folder or thin cardboard sheet with the printed pattern outside.
- Cut along the solid outline with scissors.
- Place the cut-out pattern on a table with the printed pattern facing you.
- Fold upward toward you along the dotted lines and tape the solid line edges together. This will make a triangular box with one curved side.
- Carefully use a pin or sharp pencil to punch a small hole at the cross-marked location where the two straight sides of the box meet.



Using the Protractor

Looking at your pinhole protractor, you can see that the protractor angle scale is on the curved strip, which is at right angles to a circular arc with its center at the pinhole. Under normal daytime lighting outdoors or indoors, this pinhole gives a reasonably clear view not only of the distant object, but also of the up-close angular scale.

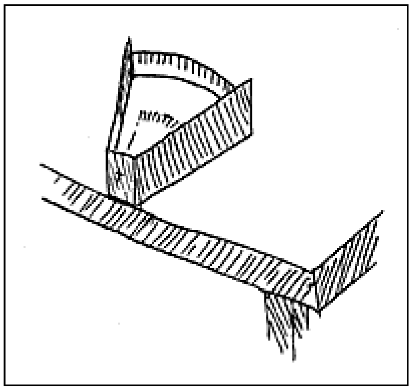


Diagram of constructed protractor

If you wear glasses, try taking them off when using the pinhole protractor. The pinhole actually takes over the function of the lens of the eye. Note that there is an ordinary protractor printed on the flat bottom of the instrument. By means of the outwardly extended lines on the flat sheet, you can see that 0 degrees, 5 degrees, and so on correspond to the same values on the curved strip.

To measure angles, follow these steps:

- Put one eye very close to the pinhole on the outside of the protractor and look through the pinhole.
- Turn the protractor so that 0 degrees on the scale is in the direction of one side of the object.
- Keeping the 0-degree mark in the direction of one side of the object, read off the coordinate of the other side on the scale. This number is the angle between the two in degrees.

The pinhole protractor is good for measuring angles to an accuracy of half a degree. Students can use the protractor to measure the angular sizes of various objects. After some exploration, students should be able to tell that angular size, physical size, and distance are related.

Estimating Distance

To understand this relationship in greater detail, students familiar with arithmetic can measure distances using the pinhole protractor and the following formula:

> *distance = 57.3 x physical size ÷ angular size (in degrees).*

The angular size is expressed here in degrees. The physical size and distance must be in the same units, such as inches or centimeters. This formula is not good for large angular sizes, but for angles less than about 20 degrees, it will give good results. The factor 57.3 is a conversion factor that changes the angular size in units called radians to a value in degrees. Students familiar with trigonometry can even derive this formula. We will test the above formula by measuring the distance to an ordinary 12-inch (30-centimeter) ruler from various positions with both a yardstick and the protractor.

- Hold the ruler horizontally against a blackboard and mark where the ends of the ruler are located.
- Write this marked length in the first row of the worksheet on p. 7. It is a good habit to always write the units (inches, centimeters, whatever) after the number.
- Go outward from the middle of the ruler, straight out from the wall, and pick three positions. The closest position should be at least 3 feet (1 meter) from the wall, so that the angle won't greater than the 20-degree formula limit. The furthest should be less than 15 feet (4.5 meters) away, so that the angular size of the ruler won't be too small to measure accurately.
- Mark these positions with masking tape at '1', '2', and '3'. Measure these distances with a yardstick and record them in the worksheet. Use the same units as for the ruler length.
- Measure the angular size of the ruler from each position using the pinhole protractor and record this in the worksheet. The angular size that you will obtain is in degrees. For example, if the physical size of the ruler is 12 inches and the angular size is 6 degrees, the distance is:

distance = 57.3 x 12 ÷ 6 = 114.6 inches = 9.5 feet

- Calculate the formula value for the distance and enter it in the last column of Table 1. How well does the estimated distance agree with the measured distance?

Now that students have tested the procedure, they can use it to measure the distance to other objects of known size -- even at distances they cannot measure directly with a yardstick, such as buildings, cars, even the Moon.

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