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Keepin' an Eye on the Sun

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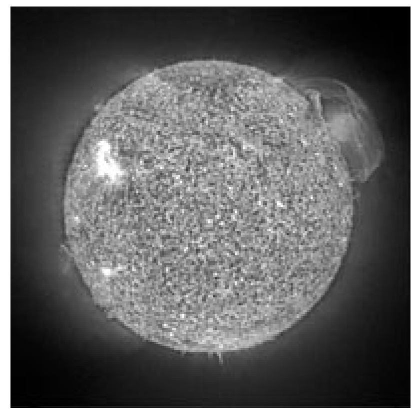
According to ancient beliefs and modern science alike, the Sun played a fundamental role in the creation of life on Earth. Our parent star is by far the largest object in our solar system-none of the planets can compete. At one hundred times the Earth in diameter, the Sun could hold about a million Earths. And majestic Jupiter, king of the planets? The Sun could swallow about 700 Jupiters! Sadly enough, however, the Sun enjoys no such distinction among the rest of the stars in the Universe. As far as stars go, the Sun is average in diameter, mass, and brightness. But it is our star, and as our distant ancestors concluded, our relationship with it is strong.



Up, up, and...back down. In a solar prominence, charged particles stream up from the Sun, spiraling around magnetic field structures poking out of the solar surface, and ultimately fall back along those structures into the Sun. In this photograph of the Sun made from NASA's Skylab space station in 1973, the prominence is almost 50 Earth diameters in size. Image courtesy of NASA.

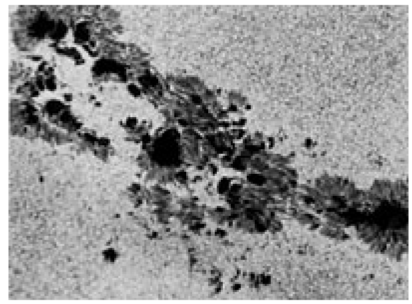
Worshipping the Sun as creator has been out of style for quite some time now, yet the Sun's formative influence has undeniably touched every living thing on Earth. Plants use the specific types of energy offered by the Sun to grow, and other creatures consume these plants for their own energy. As evolution would predict, animals' eyes sense the colors of light emitted most strongly by the Sun. Even cultural evolution exhibits Sol's influence, as Earthly motions relative to the Sun determine the day and the year.

The Earth completes exactly one rotation about its axis each day and exactly one orbit around the Sun each year. As the Earth rotates, any earthbound observer faces a different direction after a period of time, so fixed objects like the Sun or the stars around us seem to move (just as a painting on the wall would "rise" and "set" from your field of view if you spun yourself around). This explains sunrise and sunset, day and night. Climate changes across seasons can be explained by the tilt of the Earth's rotation axis. The northern hemisphere experiences summer when the north pole of the Earth tips toward the Sun, which makes our star appear high in the sky; half a year later the north pole points away, causing a northern hemisphere winter. And seasons in the southern hemisphere? Opposite to those in the north! The Sun pulls the Earth around in an orbit with gravitational attraction, in the same way a yo-yo can do an around-the-world because its string constantly pulls it toward the center of the circle. The yo-yo would fly off without the pull of the string, as would the Earth if the Sun lost its gravitational grip.

What of the Moon? It orbits the Earth just as the Earth orbits the Sun, so the relative positions of the three change constantly. About once every year and a half, the Sun, Earth, and Moon all fall on a line pointed to the Sun, the Moon briefly caught between the Sun and the Earth. When this happens, the Moon can actually block the Sun's light and one of nature's grandest spectacles results: a total solar eclipse (see "Shadow Play" in this issue). But the Sun is not totally darkened. Fortuitously for us earth dwellers, the Moon is roughly 400 times smaller than the Sun, and by coincidence it is also 400 times closer; hence, the two appear the same size in our sky. The tiny Moon can completely cover the disk of the Sun, blocking most of the emitted visible light, and reveal the Sun's faint outer atmosphere called the corona.

...a mass of incandescent gas

Like the Earth, the Sun has different layers with different properties, and like all other stars in the Universe, these layers are composed of material that is about 75% hydrogen and 25% helium by mass. Simply put, the Sun is a great ball of gas, hot enough to glow in every tier. In the very innermost part of the Sun, called its core, the temperature is about 15 million Kelvins, the density is 150 times that of water, and the pressure is over 200 billion times greater than atmospheric pressure here on Earth. This heavy, sweltering place is where the Sun's energy is produced via a process known as thermonuclear fusion. While fusion is difficult to mimic on Earth, the scorching belly of the Sun and other stars is a perfect environment for it. Here, the temperatures are high enough for hydrogen nuclei to smash together and form helium nuclei, releasing tremendous amounts of energy in various forms. Energy produced in the form of light keeps bouncing around inside the Sun, as though the Sun were made entirely of mirrors. A particle of light can take 30,000 years to reach the surface and escape! Energy in the form of small particles called neutrinos, however, can travel directly out of the Sun and into the Solar System. Neutrino observatories on Earth measure the continual wash of these tiny, fast-moving particles.



Those darned blemishes. Sunspots appear dark in contrast to the hot, surrounding photosphere. They are, in fact, quite hot; the Sun's contorted magnetic field suppresses gas motions below the photosphere in some areas, and blemish-like sunspots appear. Notice the mottled appearance of the photosphere; this is due to sub-photospheric gas motion called convection, and the size of those convecting gas parcels is about half the width of North America. Photo courtesy of National Solar Observatory/Sacramento Peak.

All that light released during nuclear reactions eventually works its way out of the Sun, and when it reaches the cold of space it starts flying. The Sun's thin, outer layers are called its atmosphere. And, like the Earth, the solar atmosphere has distinctive layers. The photosphere is the deepest atmospheric layer and is the one most easily visible to us. It can be considered the surface of the Sun, because almost all the Sun's light streams from it. A temperature of nearly 6000 Kelvins makes this gassy "surface" a little uncomfortable, though. Sitting on top of the photosphere is a thin, hot layer called the chromosphere. On top of the chromosphere sits the corona, crowning layer of the solar atmosphere.

Far more voluminous than the Sun itself, the low-density corona reaches all the way out to the planet Mercury and is composed of gas at a temperature of a few million Kelvins. Energy from the Sun drives coronal material even farther out into the Solar System. The charged particles from this swift solar wind sometimes cause magnetic storms as they blow past Earth. As a result, people at high northern and southern latitudes are treated to a spectacular show: beautiful, shimmering aurorae, also known as the northern and southern lights.

Some solar physicists are particularly interested in the corona because it harbors a great solar mystery. As one might expect, the hottest temperatures in the Sun are found in its energy-producing core, and the heat declines steadily outward toward the photosphere. Strangely enough, however, temperatures increase sharply through the solar atmosphere. Indeed, parts of the corona are nearly as hot as the core! Solar researchers have thought for several years that the heating may be due to energy transmitted up through the Sun's atmosphere by sound or magnetic waves. NASA and the European Space Agency launched the Solar and Heliospheric Observatory on December 2, 1995; recent observations by the space-based SoHO seem to indicate that magnetic waves generated near the Sun's surface travel up through the corona, depositing their energy there and making the corona hot. Because understanding the Sun is the key to understanding other stars, solar questions are among the most important in astrophysics.

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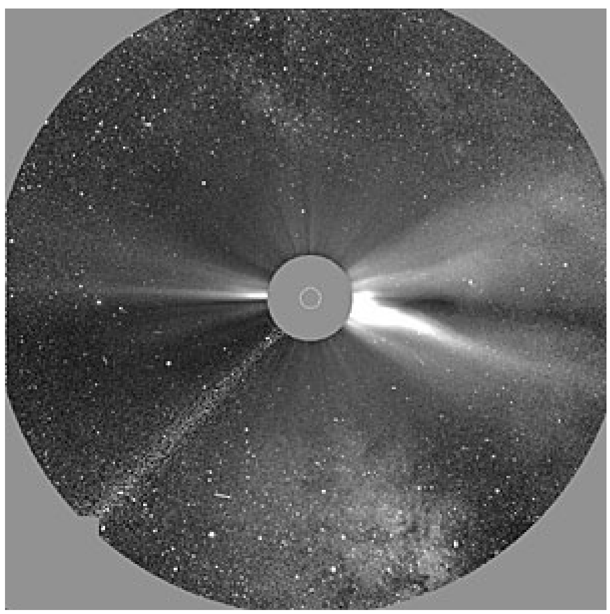
Such a Magnetic Personality

Because the Earth is solid, all parts of it must spin around the axis at the same rate. Regions near the poles must spin around once a day, the same as regions near the equator, or else the planet would fly apart. The fact that the Sun is a gas, however, lets different regions pass by one another fluidly. In this way, the equator can spin around faster than the poles, and in fact it does. A point on the solar equator takes only 26 days to travel all the way around the Sun, whereas a point near the poles takes about 10 days longer.

This differential rotation has interesting ramifications for the Sun's magnetic field. Imagine the Sun's magnetic field lines as ropes that get stretched and kinked and tangled as different latitudes of the Sun move around at different rates. This bizarre distortion of the magnetic field results in active phenomena on the surface of the Sun. Sometimes the magnetic field restricts the energy flow to the surface, resulting in cooler, darker, roughly Earth-sized patches called sunspots. Sunspots look dark only compared to the surface of the Sun; if we could somehow float a sunspot in chilly outer space we'd see the spot glow red hot.



Giving up the ghost. The Sun occasionally throws off large amounts of hot, electrically charged gas in events referred to as coronal mass ejections. Thought to be due to instabilities in the solar magnetic field, CMEs can contain tens of trillions of kilograms of gas. This particular CME was observed in December 1996, as the Sun lay in the constellation Sagittarius, by one of the instruments on the SoHO spacecraft. The circular mask in the center of the image covers the Sun's bright photosphere to permit study of the tenuous corona. Image courtesy of SoHO/LASCO consortium. SoHO is a project of international cooperation between ESA and NASA.

More violent phenomena also result from the Sun's warped magnetic field. If field lines poke an elbow out the surface of the Sun, material can travel along them in streams, creating a prominence. These huge loops of gas are typically ten times the diameter of the Earth and can last for weeks. Magnetic instabilities in the solar field cause short, violent ejections of gas called solar flares-the most explosive events on the Sun.

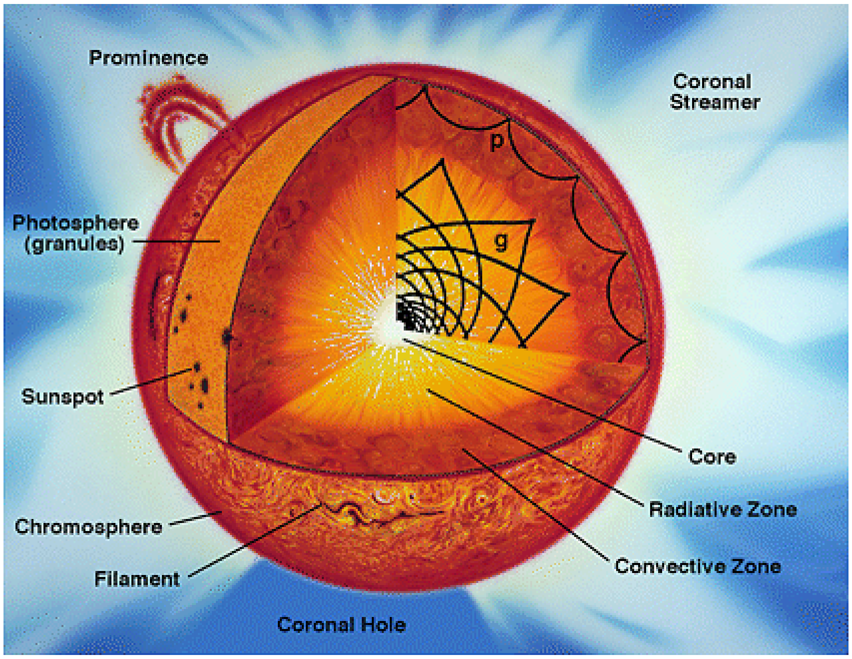
The Sun's atmospheric activity peaks about every 11 years, a pattern known as the sunspot cycle. At the low point in the cycle, called solar minimum, there are very few sunspots, and those that do appear are located far from the Sun's equator. During the next solar maximum in the year 2001, however, there may be hundreds of sunspots on the Sun at once, and several prominences or flares.

Just when you think you've got our star figured out, out leaps another provoking magnetic characteristic: orientations of the magnetic poles reverse for every solar maximum. For example, if at one maximum the magnetic north pole is "up" and the south pole "down," at the next maximum the magnetic north pole will be "down" and the south "up." So the entire solar cycle lasts twice as long as the sunspot cycle, 22 years! This is the period of time needed for the Sun to return to the exact same configuration (the same point in the sunspot cycle with the same orientation of the poles).

(carefully) Caught in the Act

Note: NEVER look directly at the Sun, even for a short time. It can cause permanent damage to your vision without causing any physical pain.

There are two ways to observe the Sun, from Earth and from outer space. The SoHO spacecraft is returning an enormous quantity of exciting data, but Earth-based observers, despite the problem of a rising and setting Sun, can also obtain excellent information-especially if they combine their efforts!



There's no chewy middle. The Sun is an enormous ball of hydrogen, helium, and a tiny amount of heavier elements, that is shaped by the inward pull of gravity. Gas pressure in our star is directed outward and balances gravity's perpetual force at every point in the star. The gas pressure is due to energy liberated by thermonuclear fusion in the Sun's core. That energy heats the gas and ultimately leaks out of the Sun through its multi-layered atmosphere. Image courtesy of SOHO/MDI/SOI consortium. SOHO is a project of international cooperation between ESA and NASA.

A network of telescopes can be used for long observations in spite of the setting Sun. People used to say, "The Sun never sets on the British Empire," because the Sun was always shining on one of the British colonies scattered about the globe. Perhaps today people should say, "The Sun never sets on GONG" (the Global Oscillations Network Group). GONG incorporates six telescopes, at sites in Australia, Hawaii, California, Chile, Africa, and India, to piece together a continuous observation of the Sun that can last for days or weeks. Long observations by GONG provide much information on helioseismology, the branch of solar physics dealing with study of periodic motions on the Sun's surface. As earthquakes on Earth tell us about the inside of our planet, vibrations on the surface of the Sun communicate much about the internal solar structure. These experimental portraits of the Sun help test theories about the general workings of stars.

There are several safe ways for anyone to observe the Sun indirectly with little or no equipment. The easiest device to use is a pinhole camera. The opening can be any shape; the round image of the Sun will appear in the shadow of the paper or cardboard if the hole is small enough. You can even make a pinhole camera with a hand, curling up a finger to make a small hole. ***Look only at the shadow, not through the hole directly at the Sun!*** The projected image will show the surface of the Sun. See "Making a Pinhole Camera" in this issue for three variations on this simple device.

The Sun can also be viewed safely through special types of filters. Do not look at the Sun through any filter unless you know it to be safe. Safe filters include the following:

- Two layers of fully exposed (fogged) and developed black and white film (color film will not provide adequate protection, nor will film on which an image has been recorded [i.e., film not completely and evenly exposed]). See "Making a Solar Filter" in this issue for detailed instructions on how to prepare the film.
- A special metal-coated piece of plastic, typically aluminized Mylar. Double-sided coatings greatly reduce the possibility of filter defects. Metal coated glass is also available. Sources for these filters include:
- Rectangular welder's glass, shade No. 14. Less dense shades (lower numbers) are not suitable for direct solar observation. Welder's glass will produce a green-colored image.

Many filters that are sometimes recommended for observing the Sun are not safe for direct-eye viewing, including a piece of glass blackened by soot from a candle, sunglasses, photographic neutral-density filters, and solar filters that operate at the eyepiece of telescopes or binoculars. Eyepiece filters are dangerous; they are placed at the point where the Sun's light is most concentrated and magnified. They can crack or even explode.

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Shadow Play: 1998's Total Solar Eclipse

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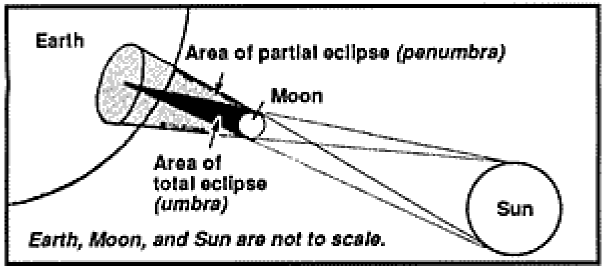
On the morning of Thursday, 26 February, amid the Galápagos Islands, the Sun will fade from view. Not the culmination of ancient prophecy, but none less mystical, Earth's small Moon will be executing a slow slide past the enormous Sun. From the middle Pacific to nearly the western coast of Africa, the Moon's shadow will sweep quickly across a little earth and a lot of sea. And anyone living in southern North America, Central America, northern South America, or on islands and cruise ships in the Caribbean Sea will, weather permitting, have the opportunity to experience the wonder of a solar eclipse. The dark, inner part of the Moon's shadow, called the umbra, will strike the Earth first in the warm Pacific waters southeast of the Hawaiian Islands and trace a smooth curve across the Pacific until Galápagos landfall. From there the shadow races toward the western coasts of Panama and Colombia, crosses them, and heads through Venezuela before it returns to water as it plunges across the Caribbean Sea. After a fleeting, dark visit to several islands there, the shadow heads out over the Atlantic Ocean, finally leaving the Earth west of Morocco and returning to the cold, familiar darkness of space.

Hiding behind a mask (almost). The Moon's orbit around the Earth is elliptical, so its distance to our planet changes. When the Moon is more distant, it appears slightly smaller in the sky, and during an eclipse, it may not completely cover the Sun's disk. Conversely, when the Moon is very close to us, it appears appears larger in the sky and can cover more of the Sun. In that situation we would not be able to see the prominence structures. Photo courtesy of NASA.

The eclipse's path is determined by the position of the Moon relative to the Earth and by subtleties in the perpetual waltz of these two bodies. Always occurring during a new Moon, a solar eclipse is visible from only limited portions of the Earth due to the inclination of the Moon's orbital plane with respect to the Earth's orbital plane about the Sun (called the ecliptic). At the time of a solar eclipse and when, say, the Moon is slightly above the ecliptic, the Moon's shadow will generally strike regions of the Earth's northern hemisphere. But the Earth is not flat, much as some might still like to believe, and the lunar shadow falls on a slightly squashed, spinning ball. This, combined with the Moon's own orbital motion, culminates in an eclipse path that gracefully curves across the world and a shadow that changes size and shape and speed during its visit. For those individuals who feel the chilling sensation of the dark umbral shadow's passage, the Sun will disappear, obliterated for up to several minutes by the Moon's disk as it covers Sol's face.

But what about those individuals who will not experience totality? They will witness a partial solar eclipse as the outer, or penumbral, shadow crosses them. A person in Coro, Venezuela, just south of the umbra's path, will see a Sun whose face is over 99% obscured, whereas persons at increasing distances from the eclipse path will see decreasing coverage of the Sun's face (e.g., someone in Nashville, Tennessee will view a Sun with 17% coverage). Near but just outside the path, the sky will reach an appearance like that at twilight. Inside the path, however, the Moon will appear to completely consume the Sun, providing anyone there with breathtaking views of the different layers of the solar atmosphere.



The inner layer of the Sun's tenuous atmosphere, the photosphere, is both the coolest and the brightest. As more and more of this "surface" is hidden by the Moon, the sky dims as Earth spins toward an unnatural twilight. The sky darkening at an ever-increasing rate, the Moon's edge will appear to leap into tendrils of fire and light as the last vestiges of photosphere are masked, its light slipping through mountains and crater rims on the ragged lunar limb. This is the one opportunity for humans to view the next, higher layer of the solar atmosphere, called the chromosphere. Immense plumes of hot gas propelled through the chromosphere appear as tiny luminous threads on the Sun's unraveling edge. But then, as quickly as it flashed into view, the thin, hot chromosphere disappears as it too is covered by the Moon. What is left is the majestic crown worn surreptitiously yet continuously by the Sun. The hottest, highest, and most tenuous portion of Sol's atmosphere is called the corona, and when the photosphere's garish light is shielded during a total solar eclipse, the corona glows in splendid radial streamers that give an eerie glow to the darkened day.

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Eclipse Watching: How to Make a Solar Filter

(adapted from Observe: Eclipses, published in 1979 by the Astronomical League and "Safe Solar Filters," by B. Ralph Chou, Sky and Telescope, August 1981)

Materials:

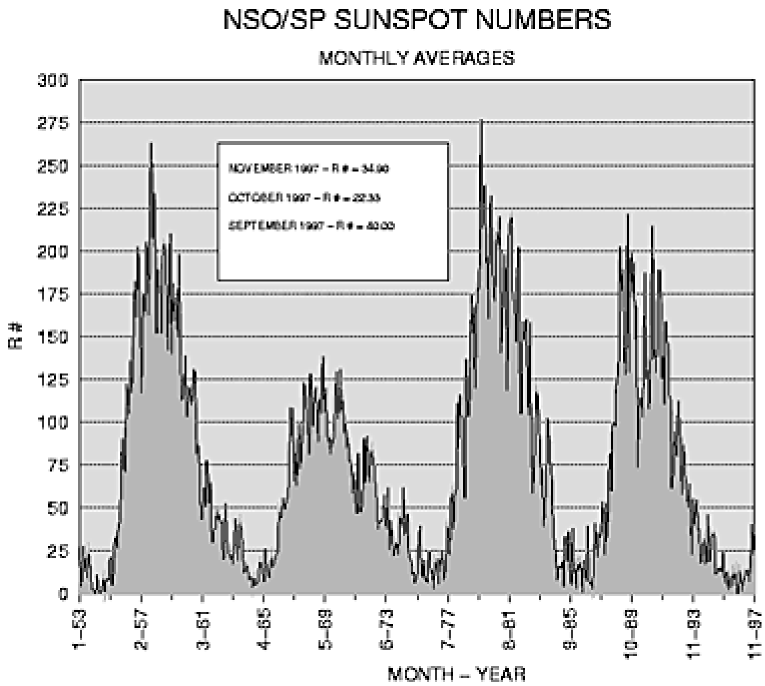
- a roll of Kodak Pan-X black and white film
- two pieces of cardboard (about 8" square or larger) to act as a holder

Instructions:

Open the roll of film, unravel it completely, and hold it for 30 seconds under a bright light. After exposing the film, have it developed normally. If you send it off for processing, include a note saying that the film is fully exposed and to be used for solar observation; request it to be developed and returned uncut. (It is important to stress this because many labs may think the film was sent in by mistake.)

Once the negatives are returned, cut them into pieces about 5 cm by 5 cm. Cut a slightly smaller square opening in the middle of both pieces of cardboard. Tape TWO pieces of film together into a sandwich, and tape this over the opening in the cardboard. Position the second piece of cardboard over the first, and tape them together. The cardboard frame will act as a shade from the bright Sun, while you safely observe through the film sandwich.

Note: A single layer of black and white film is not safe-it reduces the amount of light hitting the retina, but it does not eliminate the danger from prolonged observation of the Sun. Two layers of film effectively reduce the incoming sunlight to a safe level. Black and white film is safe because it contains silver, which absorbs sunlight, including ultraviolet and infrared light. Color film does not contain silver and is not safe. Undeveloped film is not safe.



Activity on the way. The Sun is approaching another level of high activity-called solar maximum. This period is characterized by greater numbers of sunspots, an increase in coronal activity, and, because of the relentless solar wind (a coronal product), subsequent increases in auroral activity in Earth's atmosphere. This plot of the average number of sunspots per month for the past 45 years clearly shows the Sun's 11-year sunspot cycle. Photo courtesy of National Solar Observatory/Sacramento Peak.

Classroom Activity: Pinhole Camera

Materials:

- large cardboard box
- small square of aluminum foil
- white paper
- tape
- straight pin

Instructions:

Cut a 5-cm hole in one end of the cardboard box. Tape the aluminum foil over the hole, and use a straight pin to put a very small, even hole in the foil. On the inside and at the opposite end of the box, tape a piece of white paper. Voila! You have a pinhole camera!

Sunlight enters the pinhole and a small image of the Sun will be projected on the sheet of white paper. To use your camera, stand with the Sun behind you, and hold the box over your head, the pinhole side facing the Sun. Do not look through the pinhole at the Sun. Instead, look at the image of the Sun projected on the white-paper screen. Larger boxes are going to give you larger Sun images; in addition, a larger box is going to be a more comfortable fit for your head!

As an alternate camera design, use the cardboard tubes from paper towel rolls. The tubes from hefty towels are a bit larger than those from standard towels; get one of each, and slide the smaller one into the larger. At the end of one of the tubes, tape the aluminum foil, and make a tiny pinhole. At the other end of the two-tube assembly, tape a piece of wax paper (your screen). Aim the tube at the Sun, and notice how sliding the tubes in and out changes the size of the Sun image projected on the wax paper.

Another design will provide larger images, and larger images make sunspot observations possible. Cover a flat mirror with a sheet of thick paper that has a 0.5-cm hole in it. Secure the mirror with tape or putty such that it reflects the Sun's image onto a wall or projection screen.