Chapter 5

Our Sun: Looking Good

In This Chapter

- What color is the Sun?
- Why is the sky blue, and why are sunsets red?
- What is the green flash and how does the Sun make rainbows?
- When does the Sun cause static on your radio?
- What is the Sun's spectrum like?

The Sun is too bright to safely look at it directly. We know, nonetheless, that it has its own color. Furthermore, it causes lots of colors around the sky. In this chapter, we discuss several aspects of the shining Sun.

What Is White?

The human eye is a wonderful sensor. When it sees a white page, it teams up with your brain to make it seem white, even when its color changes slightly. For example, light at sunset is reddish, but a notebook page that you hold up in the air will still look white to you.

The Sun gives off light all across the spectrum. The shortest wavelengths of light that we perceive are violet, somewhat longer wavelengths are blue,

middle wavelengths are yellow and green, and long wavelengths of light are orange and red. It is nice to think of the friendly fellow known by the acronym of ROY G BIV: red, orange, yellow, green, blue, indigo, and violet.

If you measure with an electronic meter, you would find that the Sun gives off most of its light in the yellow and green. It gives off less light to shorter and to longer wavelengths. This mixture of all the colors just as they are coming from the Sun is known as white light. It isn't exactly the same as the mixture of red, green, and blue light coming from three projectors that, when they overlap, also look white to the eye.

The human eye detects the finest detail and the faintest images using structures called rods located in the back of the retina. It detects color using the cones. These cones come in three types—ones sensitive to red, ones sensitive to green, and ones sensitive to blue. So if the cones are stimulated in the right proportions, your eye and brain perceive white.

Fun Sun Facts

In astronomy, when looking at a faint object in the sky either directly or through a telescope, you don't usually get strong enough light to activate your eye's cones. Only the rods operate, so you don't usually see color in the sky. You certainly don't see the bright colors that show in long exposures with telescopes.

To look at the Sun directly or with a telescope, you need a filter that reflects or absorbs all but about 1 part in 100,000 or 1 part in 1,000,000 of the incoming sunlight. The best of these filters have thin metal coats deposited on glass. Many satisfactory filters have metal deposited on a plastic substance known as Mylar rather than glass. Whenever you use such a filter, you should be careful that there aren't any pinholes, tears, or other defects that allow full sunlight to leak through.

These solar filters have approximately neutral density—that is, they are roughly equally dense to all colors. A safe neutral density (that is, ND) solar filter must be at least ND 5—that is, it must absorb all but 1 part in the number 1 with five zeros (100,000). And this neutral density must extend not only across the whole visible spectrum, but also into the infrared. Photographic filters, such as the Wratten series made by Kodak for use with cameras, aren't very dense in the infrared and so should not be used for looking at the Sun with your eye, even if they say ND 5.

Many of these filters aren't strictly neutral. They may let slightly more blue light through, giving the solar image a blue tinge. Many people find this effect less pleasing than that of the metal-deposited filters, which often have a slight orange tone.

Why Is the Sky Blue?

When light bounces off tiny particles, we say that it is "scattered." Its direction changes, and it can bounce around. But the shorter the wavelength, the more effectively light is scattered. So blue light scatters more effectively than red light.

This kind of scattering off small particles compared with the wavelength of light is known as Rayleigh scattering. Lord Rayleigh (1842–1919), in England, worked out the theory in the nineteenth century. (Later, he got the 1904 Nobel prize for his work on gases, including the discovery of argon.)

The dependence of Rayleigh scattering on wavelength is very strong. It varies inversely with the fourth power of the wavelength. Red light at 650 nanometers (650 billionths of a meter) is $650 \div 400 = 1.6$ times longer than blue light at 400 nanometers. But it scatters better by a factor of 1.6^4. You can do this math in your head by noting that $1.6^4 = 1.6^2 \times 1.6^2$. Since 1.6^2 is about 2.5, and 2.5^2 is about 6, we see that blue light scatters better by a factor of about 6 even though it is only a factor of 1.6 times shorter.

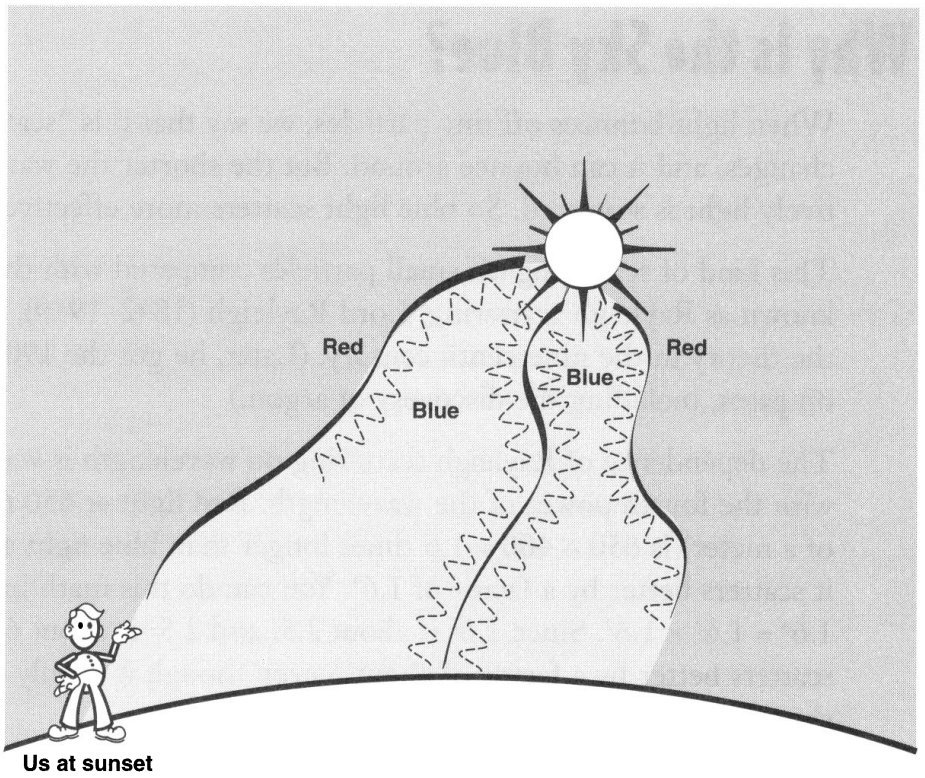
When the scattering particles get bigger compared to the wavelength of light, they don't cause Rayleigh scattering any more. Then they scatter evenly across the spectrum. So though the particles that make the sky blue are small, larger particles merely spread out the sunlight in various directions. The larger molecules of water vapor that make up clouds spread out the sunlight evenly. That is why clouds are white.

Why Are Sunsets Red?

When you look at a sunset, you are looking low on the horizon. The sunlight has traveled through much more air to get to you than it does when the Sun is overhead. As the sunlight travels through the air, it undergoes Rayleigh scattering. At sunset, that makes the sky blue for the people on the Earth between you and the setting Sun. Their blue skies subtract so much sunlight that what is left appears reddish.

If you have ever taken a photograph at sunset, you know that it turns out with a reddish cast. Sometimes that cast can be taken out in processing, but sometimes it is too strong. Still, the human eye and brain team up to see the sunlight as white even when it is really reddish.

Sunsets are red because the blue light has been scattered to make blue skies for other people.



What Is the Green Flash?

The green flash is real, though many have doubted it. Why, people say, should the Sun ever look green on the horizon? The answer lies in the bending of sunlight and in its absorption.

The Earth's atmosphere is a thin layer that curves around Earth. As sunlight passes through it at a low angle, the sunlight is bent. But the amount of bending depends on the wavelength. Violet light and blue light are bent the most, and red light is bent the least.

If you then look back at the Sun, you might, in principle, see a series of overlapping round images. The blue image would be bent the most, so when you look back along it, it would appear the highest. The red image would be bent the least, so when you look back along it, it would be relatively close to the real geometric direction to where the Sun would be if the Earth didn't have an atmosphere.

But of that vertical series of Sun images, little of the violet and blue light reaches you because it is scattered out to make blue skies elsewhere. You thus have only ROY G. When you look low in the sky, the amount of water vapor accumulates. Water vapor absorbs orange and yellow light very well. That leaves you two overlapping images: a

higher one of green and a lower one of red. As soon as the red one sets, you are left with only the green. It lasts just a few seconds, and at that point just a green rim appears at the top of the Sun. Sometimes distortion in the atmosphere makes that green rim appear to separate a bit from the top of the solar image. In any case, that green bit flashes into visibility for a few seconds.

The effect is best seen when looking out over water because then your horizon is perfect. Of course, there can't be any distant clouds that block your view of the setting Sun. Don't stare too long at the Sun at any time, including while you try to see the green flash. You don't want to injure your eyes, and, on a lesser ground, you don't want any green that you may see to be just a negative reaction in your brain to the brighter red image that has set.

A green flash can occur at sunrise as well. However, usually we don't stand out at sunrise waiting for the first glimpse of the rising Sun, and we usually don't know exactly where on the horizon to look.

Rainbows

Rainbows can be fantastically beautiful. In certain places—like Hawaii—they are very common. In other places, they are rare wonders. They result from sunlight bending and being reflected inside water droplets.

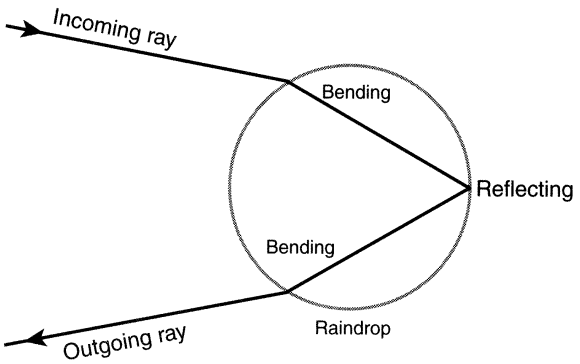
Imagine what happens when a light beam enters a raindrop. Some of the rays hit the front surface of the raindrop at an angle, so they bend as they enter. Any such bending depends on wavelength. Again, the blue rays bend more than the red rays. So, already within the raindrop, the different colors are heading in slightly different directions.

Once inside the raindrop, the light rays reflect off the inside back of the drop. Each ray, no matter what its color, reflects off at the same angle at which it hits. But since the different colors were coming in slightly different directions, the colors are still spread out after the reflection. And the bending of the different rays by different amounts as they leave the raindrop's front surface doesn't bring the rays together. They remain dispersed into the rainbow that we know and love. The band of red always lies above the band of yellow, which lies above the band of blue, and so on.

Fun Sun Facts

In 1637, René Descartes figured out how the shape of a rainbow is formed by internal reflection in raindrops. Later, Isaac Newton figured out how the colors of the rainbow are formed, incorporating his understanding of how refraction forms a spectrum. He published his ideas in 1704 in his book titled *Optics*.

If you work out the details, it turns out that the raindrops reflect the dispersed sunlight back to you in a circle about 42° across around the point opposite the Sun. Of course, we see rainbows only when the Sun is above the horizon, so the point opposite the Sun is below the horizon. That is why we don't see a whole rainbow; we see only the part that peeks up over the horizon. When the Sun is low in the sky, the rainbow extends higher up in the opposite part of the sky.



The rainbow is formed by sunlight bending as it enters and leaves a raindrop while, in between, bouncing off the back of the raindrop. The bounce is the same for light of all colors, but the amount of the bending is different for the different colors.

Fun Sun Facts

Seeing a rainbow is nice, and seeing a double rainbow can be even more rewarding. A double rainbow contains a second bow outside the first bow. To make the first bow, the light rays bounce once within each raindrop. To make the second bow, they bounce twice inside each raindrop. As a result, the order of the colors is reversed in the secondary rainbow. It is about 51° from the point opposite the Sun, but it is fainter than the primary bow.

Dogs and Pillars in the Sky

Sometimes the Sun causes rainbowlike effects in the sky that aren't from water droplets. They often come from ice crystals high in the atmosphere. Sun dogs and Sun pillars are formed in that way. Sun dogs are to the sides of the Sun, while Sun pillars are above or below the Sun.

Sun pillars form because the ice crystals that are bending and reflecting sunlight are flat. They are eight-sided, like snowflakes. As the ice crystals fall to Earth, the air resistance keeps them floating with the flat side parallel to the ground. For this reason, they are aligned enough to cause the effect of a pillar of relatively bright light, most often seen extending upward from the setting Sun. Sun pillars are the same color as the Sun, and they, therefore, can be reddish near sunrise or sunset. They can also be seen between the Sun and the ground. See, for example, antwrp.gsfc.nasa.gov/apod/ap010313.html.

Other shapes of ice crystals lead to other atmospheric effects involving the Sun. Sometimes you see a complete or partial halo around the Sun. This halo is most often 22° from the Sun, which is just greater than the width of your open hand held at the end of your outstretched arm. The inner edges of these halos are reddish.

When the ice crystals include flat ones, such as the ones that make pillars, you may see bright regions of the halo to the left and to the right of the Sun at the same altitude as the Sun. These bright spots, which can show rainbows of color, are known as sun dogs.

Static May Fade "Here Comes the Sun"

We see the Sun with our eyes using the light it gives off, but the Sun gives off radio waves, too. Whereas the sunlight is fairly steady, the radio emission from the Sun varies wildly. Giant solar flares, for example, give off bursts of radio waves that can overwhelm reception of radio stations on Earth. These flares are more common during the maximum of the sunspot cycle and in its declining phase, and powerful flares almost never occur during sunspot minimum.

Various types of radio bursts occur. Some chirp in frequency while others are more uniform across the spectrum of radio frequencies. Many of the bursts can be traced to sources high in the solar corona, since certain frequencies don't penetrate from lower down.

Radio solar observatories are rarer than optical ones, but they do exist. At Nobeyama, Japan, there is a network of dozens of small solar radio telescopes. Using computer calculations, the observations taken simultaneously with all these instruments are used to make a picture—visible to the eye—of the radio Sun. But if you just listen to the input of any one of those telescopes, what you hear sounds like just static.

Rainbows with Lines

If you spread out sunlight with a tiny prism as the light comes into your window, you see a rainbow of color. About 200 years ago, in 1802, the physicist William Wollaston thought he saw gaps in the colors as they changed from one color to another. But he reported only a handful of such gaps.

By 1814, the German optician Joseph Fraunhofer had perfected a device, called a spectroscope, for spreading out the solar spectrum. One of his improvements on previous work was to take the spectrum not of the whole Sun but only of a narrow band across it. Only the sunlight that went through a (say) vertical "slit" was spread out

into a spectrum. In such a case, we could see the spectrum of that one line of sunlight. You can imagine that the spectrum of an adjacent line of sunlight would be a similar rainbow, but displaced to the side by a slit width. By the time you took the spectrum without any slit, you would have so many overlapping rainbows of color that any detail in the color would be lost.

With Fraunhofer's spectroscope, he could study the spectrum of the Sun in detail. When he spread out the spectrum from side to side, he found that there were a handful of vertical dark lines across the spectrum. These dark lines correspond to colors at which less light is received from the Sun than at adjacent colors. We now call them absorption lines or Fraunhofer lines.

Sun Words

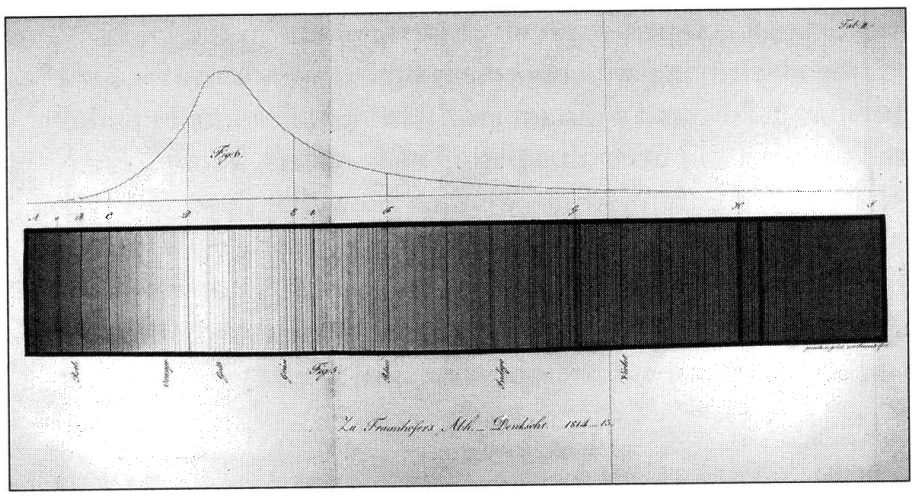
Absorption lines are locations where specific colors of a spectrum are relatively fainter than adjacent regions on either side. In the visible part of the solar spectrum, they are known as Fraunhofer lines.

Emission lines are locations where specific colors of a spectrum are relatively bright.

In general, specific colors on the spectra of astronomical or other objects that are brighter or fainter than neighboring colors are called spectral lines. When the specific colors are relatively faint, we have *absorption lines*, which are known as Fraunhofer lines when they occur in the visible part of the Sun's spectrum. When the specific colors are relatively bright, we have what are called *emission lines*. Basically, stars, including the Sun, have only absorption lines.

Fraunhofer labeled his lines starting with the red end using the letters A, a, B, C, D, E, b, F, G, and H, and he used I for the blue end of the spectrum. We still use a few of these notations. The C-line was subsequently found to come from hydrogen and is better known as H-alpha, since it is the first line (Greek alpha) in a series of hydrogen lines in the visible spectrum. Fraunhofer had noted that the wavelength of D was the same as that of sodium in his lab. On higher resolution, the D-lines turned out to be a pair of lines close together; they are known as the sodium D-lines. The H-line turns out to be an especially strong line and to arise in calcium that has been heated enough to lose one of its electrons. On Fraunhofer's original drawing, of which a hand-colored version exists in the Deutsche Museum in Germany, it is already clear that there is an almost equal dark line just to the blue of the H-line. Sometime in the nineteenth century, it began being called the K-line. We now know that both the H- and K-lines are caused by ionized calcium. We also still talk of the magnesium b-lines.

These spectral lines turn out to be the key to understanding the surface of the Sun. From which ones are there—and many or most turn out to be from iron—we can tell what chemical elements are on the Sun and in what relative abundances. We can also take the Sun's temperature with them. These Fraunhofer lines also exist on other stars, and study of the lines has led to the understanding of the distant stars.



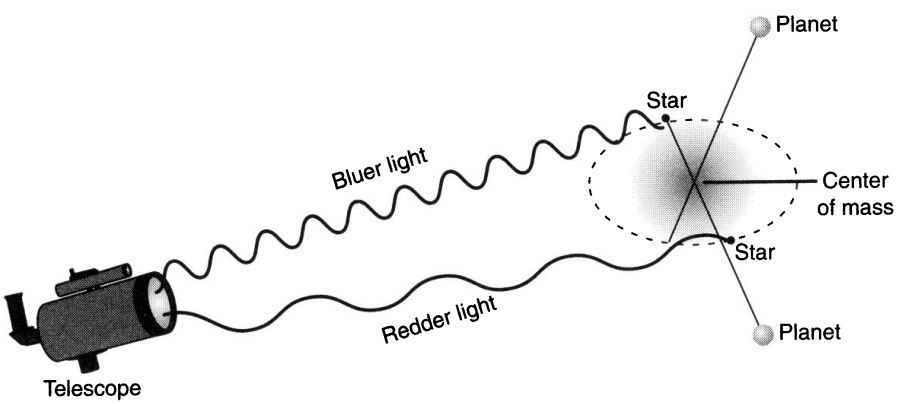
The original solar spectrum discovered by Joseph Fraunhofer in 1814, with his labels for the darkest lines that crossed the spectrum from top to bottom. The top of the diagram shows the overall brightness of the Sun at different colors.

(Jay M. Pasachoff)

Planets from Afar

In 1600, Giordano Bruno was burned at the stake in Florence, in part for talking about the "plurality of worlds." But finally, by 2000, astronomers had discovered worlds beyond our solar system, and we now know of more than 100 of them.

The discovery of most of these "exoplanets," or extrasolar planets, depends on the Fraunhofer lines. These lines are known to be at precise wavelengths. When they are observed at slightly different wavelengths, astronomers know that the gas that formed them is moving toward or away from them. When gas moves toward you, the spectral lines that it causes are shifted toward the blue end of the spectrum. When gas moves away from you, the spectral lines that it causes are shifted toward the red end of the spectrum.



More than 100 planets have been discovered around stars other than the Sun by detecting and studying the periodic changes in wavelengths of spectral lines in the light from the stars.

If you heat the gas iodine, it absorbs incoming sunlight in particularly sharp spectral lines—that is, the lines are at colors (wavelengths) that are determined very precisely. Such sets of spectral lines were compared with the spectral lines coming from distant stars. The measurements were made over periods of years, especially by a group of

astronomers in Switzerland and a competing group of astronomers in the United States. One day in 1995, the electrifying announcement came from the Swiss astronomers: A planet had been found around a distant star. The star, from its Fraunhofer lines, had been measured to go to and fro with a period of four days. From basic physics, including the third law of Isaac Newton, we thus knew that there was something orbiting that star that was going fro and to. Gravity was causing the effect. From the amount of the to-ing and fro-ing, the astronomers could get lower limits on how massive the planet must be. Similar methods were then used by both groups, and then by others, to discover the many dozens of planets of which we now know.

The Least You Need to Know

- The Sun gives off white light.
- The sky is blue because of light scattering that depends strongly on wavelength, leaving sunsets to appear red.
- The green flash occurs because of refraction and absorption of sunlight.
- The Sun gives off radio waves that cause static.
- The Sun's spectrum is a continuous rainbow with missing colors.
- We detect exoplanets by the manner in which spectral lines of their parent stars vary in wavelength.