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Gravity in the Sun:
keeping the heat on

We have seen how the Sun's gravity holds the planets in their orbits. The Sun's gravity also holds itself together. Like all stars, the Sun is a seething cauldron, its center a huge continuous hydrogen bomb trying to blow itself apart, restrained only by the immense force of its own gravity. In this chapter, we will see how the Sun has managed to maintain an impressively steady balance for billions of years. In the course of our study, we will learn about how light carries energy and we will build a computer model of the Sun.

In this chapter: we learn how the Sun holds itself up. The key is another discovery of Einstein, that light actually comes in packets called photons. These form a gas that helps support the Sun. Photons move randomly in the Sun, taking millions of years to get out. We compute the structure of the Sun, and learn why stars and planets are round, while asteroids and comets are lumpy. Finally we study the vibrations of the Sun, which reveal the details of the Sun's interior to astronomers.

Sunburn shows that light comes in packets, called photons

In this section: to understand stars, and in particular the Sun, we first learn about photons: packets of light whose energy is proportional to their frequency. The simple phenomenon of sunburn illustrates the way photons behave. The idea of a photon was first introduced by Einstein.

The Sun glows so brightly because it is hot. We can infer just how hot it is from its color. The color and temperature of the Sun are related to each other in just the same way as for hot objects on the Earth. For example, watch the burner of an electric stove as it gets hotter; it changes in color from black to red. It won't get any hotter than red-hot. But if you watch objects in a really hot fire, such as a blacksmith uses, you will see them change from red to a blueish white as they heat up.

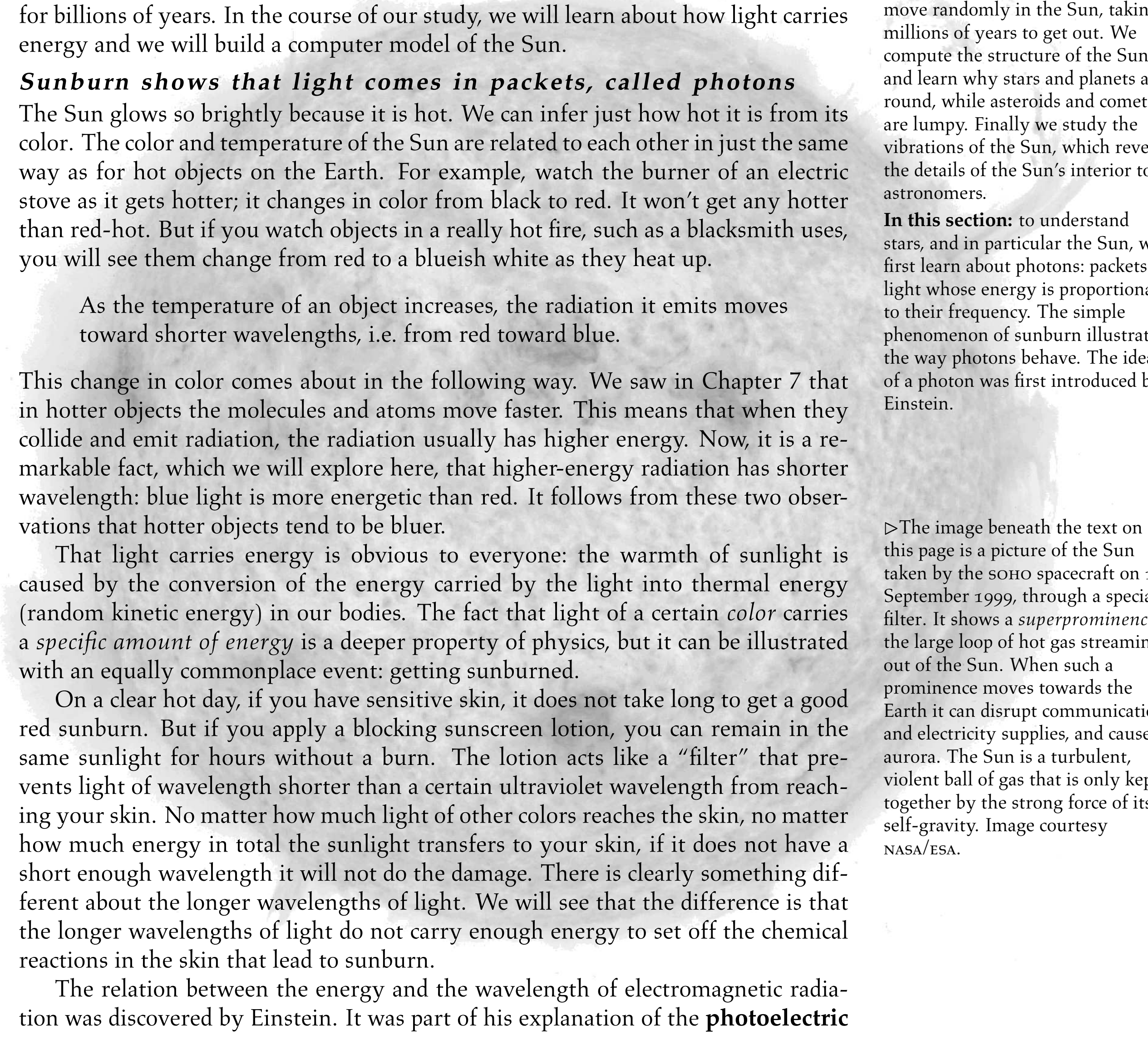
> As the temperature of an object increases, the radiation it emits moves toward shorter wavelengths, i.e. from red toward blue.

This change in color comes about in the following way. We saw in Chapter 7 that in hotter objects the molecules and atoms move faster. This means that when they collide and emit radiation, the radiation usually has higher energy. Now, it is a remarkable fact, which we will explore here, that higher-energy radiation has shorter wavelength: blue light is more energetic than red. It follows from these two observations that hotter objects tend to be bluer.

That light carries energy is obvious to everyone: the warmth of sunlight is caused by the conversion of the energy carried by the light into thermal energy (random kinetic energy) in our bodies. The fact that light of a certain *color* carries a *specific amount of energy* is a deeper property of physics, but it can be illustrated with an equally commonplace event: getting sunburned.

On a clear hot day, if you have sensitive skin, it does not take long to get a good red sunburn. But if you apply a blocking sunscreen lotion, you can remain in the same sunlight for hours without a burn. The lotion acts like a "filter" that prevents light of wavelength shorter than a certain ultraviolet wavelength from reaching your skin. No matter how much light of other colors reaches the skin, no matter how much energy in total the sunlight transfers to your skin, if it does not have a short enough wavelength it will not do the damage. There is clearly something different about the longer wavelengths of light. We will see that the difference is that the longer wavelengths of light do not carry enough energy to set off the chemical reactions in the skin that lead to sunburn.

The relation between the energy and the wavelength of electromagnetic radiation was discovered by Einstein. It was part of his explanation of the **photoelectric**



▷The image beneath the text on this page is a picture of the Sun taken by the SOHO spacecraft on 14 September 1999, through a special filter. It shows a *superprominence*, the large loop of hot gas streaming out of the Sun. When such a prominence moves towards the Earth it can disrupt communication and electricity supplies, and cause aurora. The Sun is a turbulent, violent ball of gas that is only kept together by the strong force of its self-gravity. Image courtesy NASA/ESA.

effect, which is a metallic version of sunburn. It had been observed that light falling on certain metals can eject electrons, but only if the light has a short enough wavelength. This threshold wavelength depended upon the metal. As the wavelength of the light decreased further, the electrons came out with more and more kinetic energy.

Einstein proposed that light actually comes in discrete packets, which we now call **photons** or **quanta**. Each photon carries a fixed amount of energy that can be transferred to an electron or other particle if the photon collides with it. This energy can then be converted into kinetic energy of the electron. Einstein suggested that the energy of a photon is determined entirely by its wavelength: the shorter the wavelength, the more energy. He then proposed that each metal has what is effectively an "escape speed" caused by the attraction of molecular forces inside the metal, so that if the kinetic energy given to an electron by a photon were too small, it would not attain this speed and would therefore not be ejected. Once the wavelength of the photon was short enough to give the electron its escape speed, the electron would use up a certain amount of its kinetic energy escaping, and the rest would turn up as kinetic energy of the ejected electron. This is analogous to what happens when spacecraft escape from the Earth.

▷Physicists call the minimum energy for escape the *work function* of the metal.

This neatly explained all the experiments on the photoelectric effect, but it was nevertheless a revolutionary step in physics. Physicists had been used to thinking of light as a wave. A water wave's energy depends on its height, not its wavelength: we avoid swimming in the sea if the waves are large, not if they have very short spacing! The idea that light waves carried energy in discrete amounts, which depended on the wavelength, meant that scientists had to start thinking about light as if it were a particle. This took some getting used to.

> But the experimental evidence in favor of Einstein's proposal is overwhelming, and this so-called wave–particle duality of light is something that modern physics has come to embrace, even if it is a little hard to visualize in concrete terms. It is a fundamental aspect of quantum theory. Light behaves like a wave in some respects, for example when it refracts or interferes, and like a particle in other respects, such as by carrying fixed amounts of energy.

We shall more often refer to photons in the rest of this book than to light waves. Photons make a host of astronomical facts easier to understand.

The relation between wavelength and energy that Einstein proposed is remarkable because Einstein did not need to introduce a new constant of Nature to make the theory fit the observations: he only needed to use ones that were already known to be important for the physics of light: the speed of light, c, and Planck's constant h. Planck's constant had only recently been introduced by Max Planck to describe the spectrum of the radiation emitted by hot bodies. We have already encountered it in Chapter 7, where we saw how it plays a fundamental role in the uncertainty principle. We shall introduce its importance for light here, but defer a discussion of Planck's original use for it until we study the colors of stars in general in Chapter 10.

> Einstein showed that the energy carried by a photon of wavelength λ is inversely proportional to λ, the constant of proportionality being h times the speed of light c:
>
> $$\text{energy } E \text{ of a photon} = hc/\lambda. \tag{8.1}$$

▷The Greek letter λ, pronounced "lambda", is standard physics notation for the wavelength of a wave.

This relation is described more fully in Investigation 8.1.