This text is a modified and shortened version of Chapter 7 from David A. Weintraub (2010)

Note: For readers who want to know more about what properties of matter can be understood from the light of stars, keep reading.

Colors of light

With our eyes, we distinguish that objects have distinct colors: blades of grass are green, blooming roses are red and yellow, ripe blueberries are blue, hot embers are black or red or orange or even white, a flame might be yellow or orange or blue, and the Sun is yellow. Objects have different colors for one of a few reasons: they emit light of a distinct color; they reflect light of only that color; or they emit light of all colors but more of one color than the others so that one color is dominant.

As Newton showed, white sunlight is composed of all the colors of the visible rainbow. When white sunlight reflects off a carrot, the chemicals in the carrot absorb all the incident colors of sunlight except orange. Because the orange light is not absorbed and because only orange is reflected, the carrot appears orange. A ripe lemon absorbs all colors except yellow and reflects yellow. Green leaves absorb all colors except green and reflect green. The incident solar spectrum is known as a *continuous spectrum* of visible light because it includes all the colors our eyes can see. The reflected spectrum from a leaf in summer is continuous across all the shades of green but is no longer continuous across all colors because most of the other colors have been absorbed.

If white sunlight were to pass through a gas, like the Earth's atmosphere, most of the continuous spectrum is transmitted through the gas; however, in most situations, a few very specific colors, perhaps a specific shade of red and another specific shade of yellow, will be removed from the originally continuous spectrum. When this occurs, the resulting spectrum is known as an *absorption spectrum*.

The Sun is yellow because, although it emits light of all colors, it emits more yellow light than any other color. A very hot piece of wood emits lots of light in all the colors to which our eyes are sensitive; the blend of all these colors appears white. That same piece of wood appears red if is much cooler because, at the lower temperature, it emits less violet and green and blue, so the red light is dominant. Any sufficiently dense object (such that the particles that make up the object touch or collide often) and any sufficiently large object, even of very low density, emits a continuous light spectrum; the amount of light emitted at all colors (across the entire electromagnetic spectrum, from gamma rays to radio waves) depends only on the temperature of the object. The light from such an object is known as *thermal* or *blackbody radiation*.

A thermometer for stars

A blackbody is an ideal object that emits light at all temperatures in a way that depends only on temperature. The mathematical physics for blackbodies, describing exactly how much energy is emitted at each and every possible wavelength or frequency of light for an object of a given temperature, was worked out a century ago by the German physicist Max Planck. A plot of the energy emitted by an object as a function of wavelength or frequency is known as a blackbody or Planck spectrum. On such a plot, and in all work done by astronomers, temperatures are measured on the Kelvin scale. Water boils at sea level at a temperature of 373 K (100 °C; 212 °F) and freezes at 273 K (0 °C; 32 °F).

Blackbody spectra have a number of important characteristics that are well worth noting: blackbodies emit light at *all* wavelengths, from gamma rays to radio waves; the amount of light emitted by a blackbody at each wavelength increases rapidly from the shortest wavelengths to a peak wavelength and then decreases, though less rapidly, toward the longest wavelengths; the wavelength at which a blackbody emits the most light is shorter for hotter objects, longer for colder objects; and, from identical areas of their surfaces, a hotter blackbody emits more light or energy than a colder blackbody. Extremely hot objects (millions of degrees), like disks around black holes, emit most of their light as x-rays. Objects with temperatures of tens of thousands of degrees (the hottest stars) emit most of their light in the ultraviolet. Objects with temperatures of thousands of degrees (stars like the Sun) emit mostly visible light. Objects with temperatures of hundreds of degrees (like you or me or the Earth) emit most effectively in the infrared (such objects also emit extremely faint amounts of red light that can be collected and amplified by night-vision goggles).

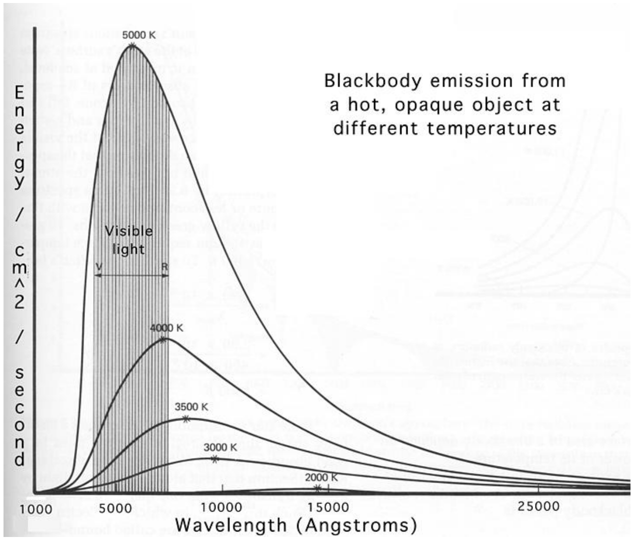

Figure 7.4: Blackbodies of different temperatures. Objects known as blackbodies emit energy in the form of light at all wavelengths (here in units of Angstroms; one Angstrom is one ten-billionth of a meter), from gamma and x-rays (left) to radio waves (right). At a given temperature, a blackbody emits more energy per second at one wavelength than at all other wavelengths. The wavelength at which a blackbody emits the most energy depends only on the temperature of the blackbody. This illustration shows blackbody curves for blackbodies of temperatures of 5,000 K (close to the temperature of the Sun; most of the light is emitted as visible light), 4,000 K, 3,500 K, 3,000 K, and 2000 K (most of the light is emitted in the infrared).

The wavelength at which a blackbody emits the maximum amount of light is determined only by the temperature of the object; this relationship, first derived by Wilhelm Wien in 1893, is known as Wien's law. Bigger objects emit more total light than smaller objects of the same temperature, but the size of the object does not affect the wavelength of light at which the object emits most effectively. Wien's law tells us that if we can measure the light from an object at enough wavelengths to determine two things — that it emits light like a blackbody and the wavelength at which the object emits the most light (its color) — we can calculate the temperature of that object.

Most stars emit light approximately as blackbodies. In practice, astronomers can measure the amount of light emitted by stars with a violet filter (i.e., measuring only the violet light), then a blue filter, then green, yellow, orange and red filters. They can observe stars with a variety of filters in the x-ray and ultraviolet and infrared and radio ranges and thereby measure the intensity of light from stars across the entire wavelength range of the electromagnetic spectrum. *By comparing these spectra with the known profiles for blackbodies of different* *temperatures, astronomers are able to determine the temperatures of stars.* In effect, because stars emit light like blackbodies, all that astronomers need do is determine the wavelength at which a star emits more light than at any other wavelength; that measurement immediately yields the temperature of that star.

Wien's law is an incredibly powerful law of physics in the toolkit of astronomers; it is a thermometer for stars. It explains why stars have different colors --- red means cooler (a few thousand degrees), yellow, like the Sun, a little hotter (6,000 degrees), blue means even hotter (twenty thousand degrees). And with Wien's law in their toolkits, at the turn of the twentieth century modern astrophysics, in which astronomers use the light of stellar objects to understand their intrinsic physical properties, was born.

Inside the atom: light interacting with matter

When light interacts with matter, three things can happen: the light can be reflected by, absorbed by, or transmitted through the matter. By understanding the structure of the atom, we can understand which of these three modes of interaction occur in a particular situation.

Atoms are composed of three fundamental building blocks, protons, neutrons, and electrons. Protons and neutrons are confined to the atomic nucleus while electrons form a cloud that surrounds the nucleus. Electrons gain and lose energy according to the rules of quantum mechanics, which govern the behavior of these and all other subatomic particles. An electron can gain energy by absorbing a photon and lose energy by emitting a photon. If an electron is *free*, that is if it is not *bound* in orbit around a nucleus, it is permitted to absorb or emit a photon of any energy; however, if the electron is in a bound orbit within an atom, it is only able to absorb (or emit) photons that contain the exact energies that would allow the electron to jump upwards (or drop downwards) to distinct, higher (or lower) energy orbits around the nucleus or to absorb any photon with enough energy to completely free it from its bound state. If, for any reason, an electron drops from a higher to a lower energy orbit, it emits a photon with an exact energy. Since a photon with that energy has a unique wavelength (or frequency), this electron emits a photon with an exact color.

The rules of quantum mechanics determine the possible energy levels for every element; these energy levels are determined by the number of protons and neutrons in the atomic nucleus. Every atom of carbon-12 in the universe is identical — six protons and six neutrons in the nucleus — and the rules of quantum mechanics are identical for every one of these ^{12}C atoms. These rules determine a distinct set of energy levels separated by well defined energy differences that the six electrons in a ^{12}C atom may occupy. In a ^{13}C atom, the spacings of these energy levels will be very slightly different. Since each energy difference corresponds to a unique wavelength of light, every isotope of every element is permitted to absorb or emit only those colors of light. The permitted colors for ^{12}C are like a set of fingerprints, a spectral signature, that distinguish ^{12}C from ^{13}C or ^{238}U. Oxygen atoms have a set of permitted colors that are unique to oxygen, iron atoms have a set of permitted colors that are unique to iron, and every other atom and every isotope of every atom and every molecule has a quantum mechanically determined spectral signature.

If we had a tube of gas, or a lamp, filled only with sodium atoms and if we were to heat up or run an electric current through that tube, the electrons would absorb energy, moving to higher energy orbits. These higher energy orbits are unstable so the electrons would then emit photons and drop down to lower energy levels. When the sodium gas emits photons, we say that the sodium gas is glowing; this glowing gas emits light at only a few distinct, well separated wavelengths. We call the light from such a gas an *emission spectrum* made up of distinct emission lines.

If a cold cloud of sodium gas were located in between us and a distant source of continuous light, the photons from the continuous spectrum, for example from a star, would have to pass through the sodium cloud in order to reach our eyes. Because each photon carries energy, these photons in the continuous spectrum become a heat source for the sodium gas. But the sodium gas can absorb light at only a few distinct wavelengths corresponding to the energy differences between permitted electron levels for sodium atoms. As a result, the light that enters the sodium cloud contains all colors, continuously across all wavelengths, but the light that emerges from the cloud is missing light at those few distinct wavelengths at which the electrons in the sodium atoms are able to absorb light. The result is a continuous spectrum with a few distinct colors missing. We call this spectrum an *absorption spectrum*.

This phenomenon of the absorption of a few distinct colors of light by a cold cloud of material that lies in between the continuous light source and our telescopes is exactly what Fraunhofer observed toward the Sun, Castor, and Sirius. In a star, the source of continuous light, the layer that emits most of the light, is called the photosphere. The gas cloud in between us and the light source in the Sun is composed of the tenuous outermost layers of the Sun's atmosphere, in which the gas is slightly cooler and much less dense than the gas that makes up the photosphere. Light from the solar photosphere passes through the outermost layers of the Sun in order to escape from the Sun; in doing so, some of that light is absorbed by the elements in these uppermost layers. The resulting spectrum is missing light at discrete wavelengths; the places where the light is missing are the black lines seen by Wollaston and Fraunhofer. The outermost layers of the atmospheres of Castor and Sirius reveal slightly different elemental signatures from the Sun. These differences are due only in small part to actual differences in the chemical abundances in the atmospheres of these stars. The most important reasons for the different spectral signatures are that the gases in the outer atmospheres of Castor and Sirius are at slightly different temperatures than the gases in the outermost layers of the Sun. The temperature of the gas in turn determines the photon energies (manifest as spectral lines) at which the gas can absorb. Since, for each star, the set of dark lines fingerprint both the elements that are present and the temperature of those elements in the absorbing outer layer of the atmosphere of that star, the spectra of Castor and Sirius show sets of dark lines that differ from the dark lines seen in the solar spectrum.

The Stephan-Boltzmann law

Experience has taught us that if we have two objects of different sizes but with the same temperature, more energy is emitted by the larger object. For example, if we wish to boil a pot of water on an electric stove, the pot will boil more quickly if we place the pot on a large heating element rather than on a small one, assuming both heating elements are at the same temperature setting. Experience, however, also has taught us that the smaller electric heating element with the temperature control set on 'high' can heat up our pot of water as quickly as can the larger one when the temperature control for the larger one is set on 'low.'

These two pieces of common sense have been quantified by physicists as the *Stephan-Boltzmann law*: the total energy released per second by an object (known as the luminosity) depends both on its temperature and its emitting surface area. If the temperature goes up, the luminosity goes up dramatically (if we double the temperature, the luminosity becomes 16 times greater); if the object gets bigger and thus has a larger surface from which to emit light, the luminosity increases (if we double the surface area, we double the luminosity).