Appendix B: Why and how stars radiate

Both the amount of light generated and the wavelength spectrum of light that an object like a star emits will depend on the physical properties of what's emitting the light. The spectrum of starlight is generally very complex on close examination, but the physics responsible for it can be broadly generalized into two processes: continuum emission, and line emission and absorption.

Continuum emission is any physical process that emits photons having a broad range of different wavelengths. As an example, think of the band of light that you see when you hold a prism in sunlight — you see several bands of color with red, orange, yellow, blue, indigo, and violet. All of those colors are present in sunlight at the same time, but you don't see them individually — the Sun simply looks white.

Blackbody radiation

A special kind of continuum emission is blackbody radiation, emitted by all objects — any objects — with temperatures above absolute zero. The amount of light and the wavelength distribution of photons in the blackbody spectrum depend on one parameter: the temperature. The key things to remember are that if one star is hotter than another, (1) it will emit more light overall, and (2) the spectrum of light it emits will have more light at shorter wavelengths. If you have two stars whose physical sizes are the same and are the same distance away from us but one is at 10,000 K and the other at 5,000 K, the hotter star will be brighter (more light), and bluer (more emission at shorter wavelengths). Thus you can use starlight to take the temperature of a star without touching it — a neat trick! The equations describing blackbody radiation were worked out by Max Planck early in the 20th century, and you'll often see blackbody radiation referred to as *Planck radiation*.

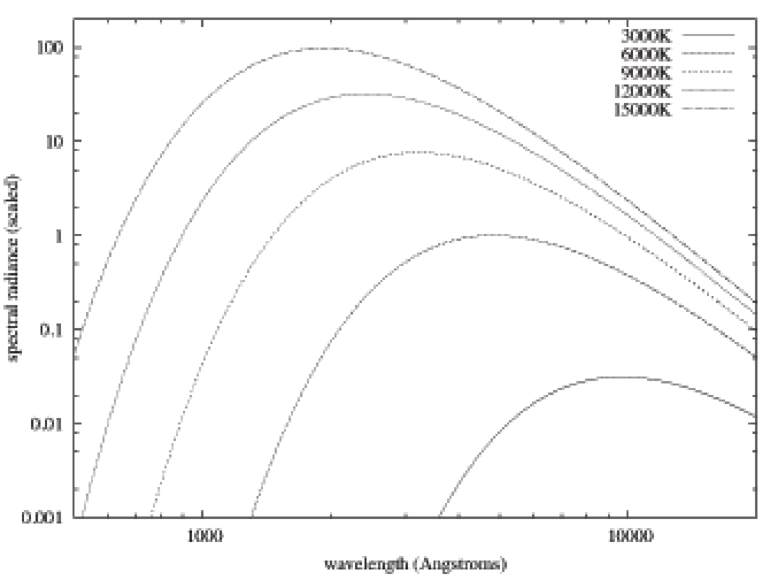

Figure B.1 – Black body spectra scaled to the peak spectral radiance of a blackbody at 6000 Kelvin. The Sun's effective temperature is about 5774 Kelvin. That of an A0 star is about 10,000 Kelvin, while that of an M star is below about 4000 Kelvin. Compare the bandpasses of filters shown in Figure 3.1 with the curves shown here.

There are a few concepts related to blackbody radiation that are very useful in stellar astrophysics. First, Wien's Law is a simple equation that gives you the wavelength at which a black body emits the most light (i.e. the peak of the blackbody spectrum):

$$\lambda_{max} = b/T$$

where λ is the wavelength, T is the temperature of the blackbody, and b is a constant (known as *Wien's displacement constant*). You can derive this using the equation of a blackbody, and determining where the curve is maximum: you determine the temperature and wavelength at which the derivative is zero. This is a really handy equation, because it lets you roughly estimate the temperature of any blackbody–like object by simply measuring where the peak of its spectrum is. Many stars behave so similarly to blackbodies that this is straightforward to measure; where it breaks down are for stars that have such strong atomic or molecular absorption that their optical spectra don't match a blackbody very well. (This often happens for M stars whose spectra peak in the near–IR anyway.)

Another relation is the Stefan–Boltzmann Law, which provides a simple relationship between the energy flux per unit area from the surface of a black body and its temperature:

$$f_{bol} = \sigma T^4$$

where f_{bol} is the total energy flux per unit area, T is the temperature, and σ is a constant (the Stefan–Boltzmann constant). The hotter a blackbody gets, the more total energy it emits. Again, this yields another interesting astrophysical application. You may be able to estimate the effective temperature a star by some means (photometric, or spectroscopic). The total luminosity (the light emitted in all directions) by a blackbody is simply this quantity f_{bol} times the total surface area: $4\pi R^2$. Combining these two things, you get the interesting equation

$$L_{bol} = 4\pi R^2 \sigma T^4$$

There are a few potentially interesting quantities there, namely the luminosity (which can be tied into the distance to the star) and the radius of the star. This is important astrophysically; the luminosity of a star is proportional to both its effective temperature and to its radius. Spectral types also include *luminosity classes* from *dwarf* to *supergiant.* A star might have an effective temperature of 4000 K, but there will be a huge difference in luminosity depending on whether its radius is that of a dwarf star or a supergiant.

Line emission and absorption

The second process, line emission and absorption, are two things caused by the same physical process — the emission or absorption of individual photons by atoms. Atoms are composed of nuclei (protons and neutrons) surrounded by electrons having very specific orbits. The orbits of these electrons correspond to specific energy levels. If an electron transitions from a higher energy level to a lower one, it will release the resulting energy difference as a photon with that energy. Since wavelength corresponds to energy, these electron transitions correspond to specific wavelengths of light. These wavelengths — or combinations of wavelengths — are unique to each atomic species. If you have a sample of hydrogen gas and excite it (say in a fluorescent tube), it will emit light at several discrete wavelengths corresponding to the electron energy levels of a hydrogen atom. Likewise if you have a sample of nitrogen, sodium, or neon gas (all common in fluorescent bulbs) they'll have different spectra. (This is why "neon signs" have different colors — they use different gases.)

The inverse of emission is absorption: if you have a photon of the right wavelength to excite an atom that has an allowed electron transition with just the right energy, the atom will absorb the photon. If you have a source of continuum emission (like the photosphere of a star) along with some gas that can absorb energy (like hydrogen, calcium, iron, or other elements in a star's atmosphere), the star's spectrum would look like a blackbody with some wavelengths reduced or missing. So when you take a spectrum of a star, you'll see mostly a continuum of light, but with dark bands appearing along the dispersion axis. The amount of absorption that you see depends on many different factors including the abundances of different atomic and molecular species, and the temperature of the star. A–type stars for example are defined as having the strongest absorption lines of hydrogen in their spectra. As another example, molecular absorption occurs in cool, M–type stars, and the kind of absorption you see depends on whether the star is richer in oxygen or carbon.

The astrophysics of radiation and radiative transfer is a very rich subject. Much of what was discussed above was laid out even before the golden age of quantum mechanics by the 19th century physicist Gustav Kirchhoff, and are summarized by Kirchhoff's three laws of radiation:

1) Hot, solid (or optically thick) objects emit a continuous spectrum.
2) A hot, optically thin gas emits light at discrete wavelengths characteristic of the chemical composition of the gas.
3) A continuous spectrum passing through a cool, optically thin gas will show absorption lines characteristic of the chemical composition of the gas (and at identical wavelengths to the emission lines that would appear if the gas were hot).

Kirchhoff outlined these rules in the 19th century, before atomic physics and quantum mechanics were understood. But for many cases of interest in variable star astronomy, these rules broadly describe everything you'll see, and the mathematical models of how light is created and how it propagates in a physical system are rooted in Kirchhoff's laws.

We won't cover spectral analysis in this manual, but it is possible to use observation and measurement of the strengths of spectral lines in a star to figure out what the star is made of. Atomic line measurement in the laboratory was and still is a major field in laboratory astrophysics. Absorption and emission lines will change their appearance in a complicated way that depends on relative abundances in the plasma, the temperature (and temperature structure when looking through a thin gas), and pressure. Some lines and groups of lines are so strong and prominent that they serve as proxies for the overall "metal abundance" (i.e. the abundance of everything except hydrogen and helium). In some cases, these can be so strong that they can even be detected in broad–band light, and thus can be detected with filtered photometry rather than spectroscopy.

Other processes

There are other sources of radiation, including magnetic fields (especially important in active stars that generate X–rays), nuclear reactions, and radioactive decay (which power the interiors of stars and are also responsible for the energy that powers supernovae and their light evolution). Many variable stars will have multiple sources for radiation and absorption. As an example, the UV Ceti stars are low–mass, young dwarf M stars, usually very cool. These objects are generally very faint since their cool temperatures mean they radiate a relatively small amount of light, mostly in the red and infrared. However, they can also emit enormous amounts of blue, ultraviolet, X–ray, and even gamma–ray radiation in very short bursts due to magnetic reconnection events in their atmospheres analogous to solar flares on our own Sun. These stars are naturally very faint in blue, so when large flares occur, they may have enormous amplitudes in blue light, but relatively little in red. A bright flare may have a B–band amplitude of 3 or 4 magnitudes, but much less than a magnitude in R– or I–band.

The physics of radiation is one of the earliest courses a student in astronomy would take, and while it isn't required to be an observational astronomer, knowledge of radiative processes may provide you with some insight into what you're observing. One particularly useful book on the topic is George Rybicki and Alan Lightman's *Radiative Processes in Astrophysics*. A detailed reference on spectral lines and stellar spectra is David Gray's *The Observation and Analysis of Stellar Photospheres.*