**Photons and Other Messengers**

## 1. Why photons?

**Ask class:** most of our information about the universe comes from photons. What are the reasons for this? Let's compare them with other possible messengers, specifically massive particles, neutrinos, and gravitational waves.

- Photons have a small cross section, but not too small. Neutrinos and gravitational waves sail through the universe with almost no interactions. That means that if we could detect them, they would give good directional information about their sources, which combined with energy/frequency resolution could potentially tell us quite a lot. However, they also sail through detectors for the most part, so only exceptionally energetic events can carry information via these channels. Massive particles have the opposite problem. Electrons, protons, and nuclei can be accelerated to high energies, but they are curved by the Galactic magnetic field and slam into air molecules (or go all the way through detectors), so some information is lost. Again, the best observations can come only from highly energetic sources.
- All kinds of objects can emit photons. Heat is all that is needed, but many other processes produce photons as well (this is fundamentally because the electromagnetic interaction is pervasive and relatively strong). In contrast, significant production of gravitational waves requires fast motion of large masses, and production of high energy particles needs large potential drops or other acceleration mechanisms. Neutrinos are actually produced pretty commonly (hydrogen fusing into helium generates them, as does the collapse of the core of a massive star), but not enough to compensate for their extremely low cross section.
- Detectors can measure with precision many aspects of photons. These include energy, direction, time of arrival, and polarization. In principle these quantities can also be measured for the other messengers, but in practice such measurements are at much worse precision than is usually available for photons.

## 2. Photons in a vacuum

Of course, there are some phenomena that are easiest to characterize using gravitational waves, neutrinos, or massive particles, but for the above reasons we will focus first on photons. We will start by considering photons in a vacuum, then recall interactions with matter at low energies before considering high-energy interactions specifically.

**Radiation in vacuum:** Consider radiation when there is no matter present. In particular, consider a bundle of rays moving through space. **Ask class:** what can happen to those rays in vacuum? They can be bent gravitationally, or redshifted/blueshifted in various ways (Doppler, gravitational, cosmological). In this circumstance, it is useful to recall Liouville's theorem, which says that the phase space density, that is, the number per (distance-momentum)$^3$ (e.g., the distribution function), is conserved. For photons, this means that if we define the "specific intensity" $I_\nu$ as energy per everything:

$$I_\nu = \frac{dE}{dA\,dt\,d\Omega\,d\nu}\ , \tag{1}$$

then the quantity $I_\nu/\nu^3$ is conserved in free space. The source of the possible frequency change could be anything: cosmological expansion, gravitational redshift, Doppler shifts, or whatever. The integral of the specific intensity over frequency, $I = \int I_\nu\,d\nu$, is proportional to $\nu^4$.

One application is to the surface brightness. This is defined as flux per solid angle, so if we use $S$ for the surface brightness, then $S = I$. **Ask class:** how does surface brightness depend on distance from the source, if $\nu$ is constant? It is independent of distance (can also show this geometrically). However, **Ask class:** how does the surface brightness of a galaxy at a redshift $z$ compare with that of a similar galaxy nearby, assuming no absorption or scattering along the way? The frequency drops by a factor $1 + z$, so the surface brightness drops by $(1 + z)^4$. This is why it is so challenging to observe galaxies at high redshift. Note that in a given waveband, the observed surface brightness also depends on the spectrum, because what you see in a given band will have been emitted in a different band (these are called K-corrections).

Another application is to gravitational lensing. Suppose you have a distant galaxy which would have a certain brightness. Gravitational lensing, which does not change the frequency, splits the image into two images. One of those images has twice the flux of the unlensed galaxy. Assume no absorption or scattering. **Ask class:** how large would that image appear to be compared to the unlensed image? Surface brightness is conserved, meaning that to have twice the flux it must appear twice as large. This is one way that people get more detailed glimpses of distant objects. Lensing magnifies the image, so more structure can be resolved.

This is an *extremely* powerful way to figure out what is happening to light as it goes every which way. The specific intensity is all you need to figure out lots of important things, such as the flux or the surface brightness, and in apparently complicated situations you just follow how the frequency behaves.

## 3. Low-energy photons

Now we need to consider how low-energy (say, UV and longward) photons can interact.

**Radiative opacity sources: Ask class:** what are the ways in which a photon can interact? Can be done off of free electrons, atoms, molecules, or dust. Specific examples include:

- Scattering off of free electrons. At low energy, this process is elastic (the photon energy after scattering equals the photon energy before scattering), and is called Thomson scattering. This cross section is useful to remember: $\sigma_T = 6.65 \times 10^{-29}$ m$^2$.

- Free-free absorption. A photon can be absorbed by a free electron (i.e., one not in an atom) moving past a more massive charge (such as a proton or other nucleus). The inverse process, in which a photon is emitted by an accelerating charge, is called bremsstrahlung.
- Atomic absorption. The two main types are bound-free (in which an electron is kicked completely out of an atom by a photon) and bound-bound (in which an electron goes from one bound state to another). Free-free and bound-free absorption cross sections tend to decrease with frequency like $\omega^{-3}$ (in the bound-free case this of course applies only above the ionization threshold). Bound-bound absorption is peaked strongly around the energy difference between the two bound states.
- Molecular absorption. The extra degree of freedom associated with multiple atoms in a molecule allows for vibrational and rotational transitions. For relatively simple reasons, there tends to be a strong ordering of energies: atomic$\gg$vibrational$\gg$rotational.

**Ask class:** why haven't we talked about interactions of photons with protons or other nuclei? Because protons are much tougher to affect with the oscillating electromagnetic fields of photons. In particular, since they're more massive and $e/m$ is smaller, the resulting acceleration is less and the radiation (hence cross section) is tiny by comparison to protons. For comparison, though, the scattering cross section off of protons is $\approx m_e^2/m_p^2$ less than off of electrons. That's a factor of almost 4 million. So, for most purposes we can ignore photon-nucleon interactions.

At higher energies (X-ray and beyond), other things can happen to photons. For example, electron recoil after scattering can be significant, which by energy conservation lowers the energy of the photon and also happens to decrease the cross section. At very high energies, photons can actually produce electron-positron pairs. We will see applications of this in the very early universe, when the light nuclei were formed.

### Thermal Emission

A special and important case is one in which the radiation and matter are in thermal equilibrium. This gives a universal and exact solution and was the problem that let to the first glimmerings of quantum mechanics. Still, in any given problem you need to consider carefully whether the radiation and matter are in thermal equilibrium or whether nonthermal processes are important.

Let's imagine an enclosure at temperature T. We have radiation in the enclosure, and we wait a long time until equilibrium has been achieved. Note that there is no conservation law for photons, so they can be created or destroyed by many processes (equivalently, we say that photons have zero chemical potential). From thermodynamics, the specific intensity that we get must be independent of the shape of the enclosure. Otherwise, you could take two enclosures at the same temperature but with different shapes, and when you put them in contact energy would flow from one to the other, in violation of thermodynamics. Thus, the specific intensity in thermal equilibrium depends only on the temperature. This argument also shows that the specific intensity in equilibrium must be isotropic.

We will now skip ahead a bit. Various books (e.g., "Radiative Processes in Astrophysics" by Rybicki and Lightman) give some interesting derivations about blackbody radiation, from classical thermodynamics as well as quantum arguments. The quantum argument, which Planck used to derive the blackbody function (aka the Planck function), is particularly cute, and relies on photon modes being required to fit exactly (integral number of wavelengths) within a box, hence quantizing the photon energies. This was the first time that anyone had done that, and it marked a transition from classical to quantum theory that Einstein followed up five years later with the photoelectric effect. I recommend that you read the derivation, but let's focus now on properties of the function itself.

**Properties of the Planck Function**

A blackbody emits a flux (energy per area) of $\sigma_{\rm SB}T^4$, where $\sigma_{\rm SB} = 5.67 \times 10^{-5}$ erg cm$^{-2}$ K$^{-4}$ is the Stefan-Boltzmann constant. The Planck blackbody function is

$$B_\nu(T) = \frac{2h\nu^3/c^2}{\exp(h\nu/kT) - 1}\ , \tag{2}$$

or with wavelength $\lambda = c/\nu$ instead of $\nu$ as the primary variable,

$$B_\lambda(T) = \frac{2hc^2/\lambda^5}{\exp(hc/\lambda kT) - 1}\ . \tag{3}$$

A critical aspect of this for cosmology is (drum roll please):

- If you shift the frequency of every photon by the same factor $f$, then you still have a blackbody, of temperature $f$ times the original temperature. Among other things this means that a redshifted blackbody is still a blackbody.

Let's look at some limits of the Planck expression.

*Low frequency, $h\nu \ll kT$.*—The exponent is much less than unity, so $B_\nu(T) \approx 2\nu^2 kT/c^2$. **Ask class:** there is a fundamental constant missing here; what is it? The Planck constant $h$, of course! This leads to an important point that will allow you to check some equations. The Planck constant will appear if and only if quantization is important. In the same way, $c$ appears if and only if special relativity is important, and $G$ appears if and only if gravity is important. So why isn't quantization important here? In the low-frequency, or Rayleigh-Jeans, limit, there are many photons. We therefore have a classical description. However, it was noticed immediately that if this expression continued to be valid for arbitrarily high frequency the energy would diverge (this was called the "ultraviolet catastrophe"). In the low-frequency limit the form of the Planck function (a power law, logarithmic slope 2 in frequency) is independent of the temperature.

*High frequency, $h\nu \gg kT$.*—Here the exponent is much greater than unity, so $B_\nu(T) \approx 2h\nu^3/c^2 \exp(-h\nu/kT)$. Now the Planck constant does appear. It's because in this limit (the Wien limit), there are very few photons and hence their discrete nature matters.

Here are some other interesting and important facts. First, there is a photon frequency at which $B_\nu(T)$ peaks, and it's at $h\nu_{\rm max} = 2.82kT$, give or take. Incidentally, you could derive that the peak energy has to be proportional to $kT$ simply by noticing that the only way you can get something with dimensions of energy out of $h, c, k$, and $T$ is by $kT$! Score one for dimensional analysis. Moving on, although the peak frequency changes, $B_\nu(T_1) > B_\nu(T_2)$ for *all* frequencies if $T_1 > T_2$ (see Figure 1).

Finally, there are some characteristic temperatures that are defined in astrophysics to relate a given arbitrary spectrum to the blackbody spectrum.

*Brightness temperature.*—This is the temperature a blackbody would have to have to give the observed specific intensity at a given frequency: $B_\nu(T_b) = I_\nu$. This is especially common in radio astronomy, where because of the low frequencies you're usually in the Rayleigh-Jeans limit, so $I_\nu = (2\nu^2/c^2)kT_b$.

*Color temperature.*—This is the temperature of a blackbody that gives the same *slope* for the spectrum as the observed slope. This is useful whenever you don't know the absolute flux, which is the case if you don't know the distance to the object (as an example).

*Effective temperature.*—This is the temperature of a blackbody that gives the same frequency-integrated intensity as the observed one, radiated at the source. That is, $\sigma_{\rm SB}T_{\rm eff}^4 = F = \int I_\nu \cos\theta d\nu d\Omega$.

## Intuition Builder

In the last class, when we discussed what other wavebands tell us about cosmology, we did not mention the extreme ultraviolet (say, with wavelengths below about 900Å). Why is that?

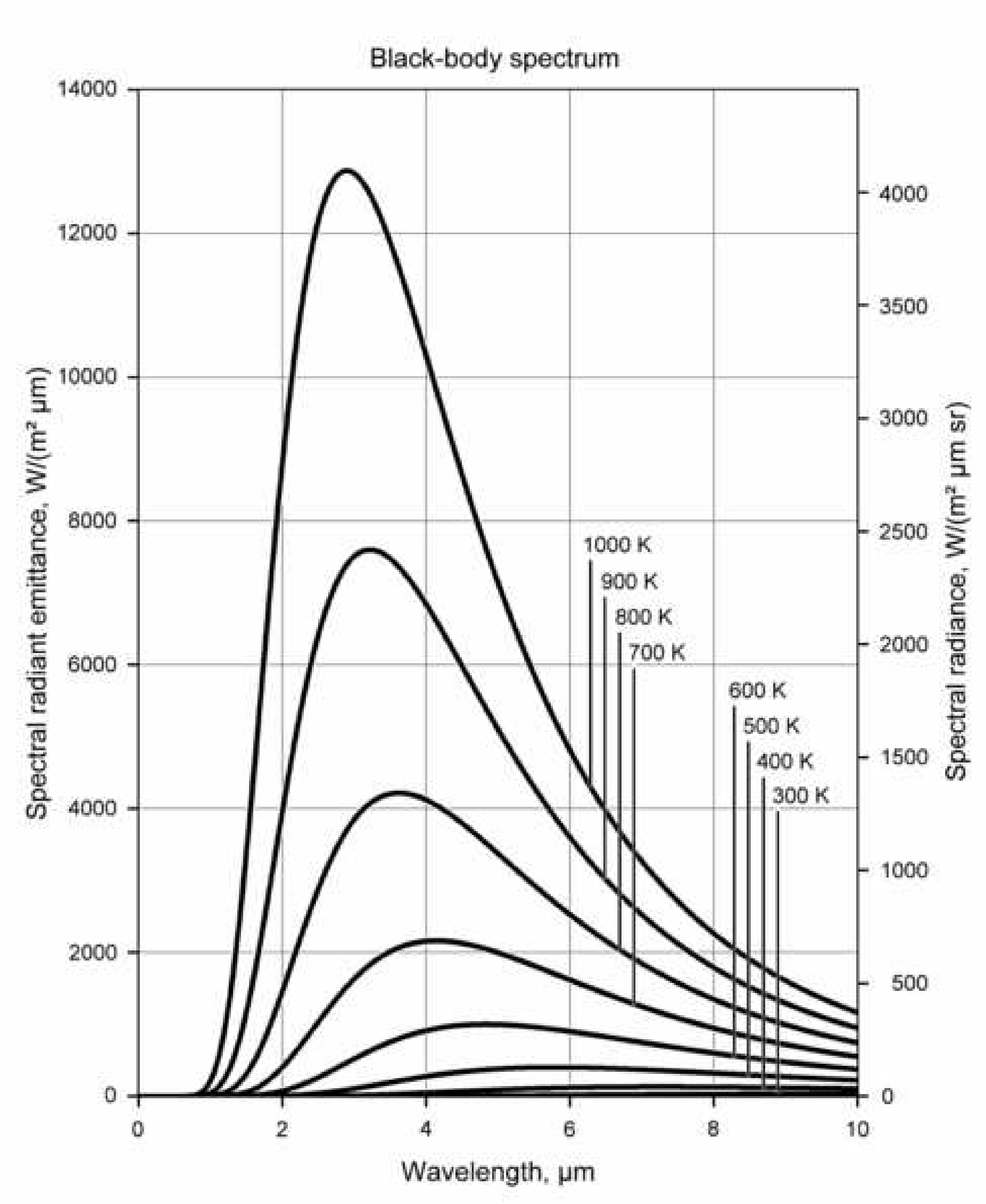


Fig. 1.— Blackbody curves for different temperatures. All the curves are scaled versions of a single master curve; note that at higher temperatures the spectral peak is at higher energies, but the flux is higher at *any* photon energy for a higher temperature. From http://commons.wikimedia.org/wiki/Image%3ABlackbodySpectrum_lin_150dpi_en.png