1 Wednesday, September 21: Introduction

This course deals with continuum radiation processes of astrophysical interest. (Processes that produce spectral lines, rather than continuum radiation, are dealt with in Astronomy 823: Theoretical Spectroscopy.) The nature of electromagnetic radiation, otherwise known as "light",[1] was long a subject of debate. Isaac Newton, in the 17th century, believed that light consisted of a stream of particles. In the early 19th century, however, Thomas Young demonstrated that light showed the properties of diffraction and interference, and thus had to consist of waves. In the early 20th century, though, Albert Einstein showed that the photoelectric effect can only be accounted for if light consists of a stream of particles, called "photons". We can take advantage of the wave/particle duality of light, and treat it either as a stream of particles or as a propagating wave (whichever makes the solution to a given problem easier!)

When we think of light as a wave, its wavelength is

$$\lambda = c/\nu \ , \tag{1}$$

where ν is the frequency, and $c = 3.0 \times 10^{10}\,\mathrm{cm\,s^{-1}}$ when the light is propagating through a vacuum. When we think of light as particles, the energy of an individual photon is

$$E = h\nu \ , \tag{2}$$

where Planck's constant is $h = 6.6 \times 10^{-27}\,\mathrm{erg\,s}$ in cgs (centimeter, gram, second) units. Note that Planck's constant is a small number, and thus each photon carries only a small amount of energy.

Electromagnetic radiation consists of a spectrum of light, ranging from short wavelength to long (that is, from high frequency to low, or from high photon energy to low). By convention, the spectrum is divided into γ rays, X rays, ultraviolet, visible, infrared, microwave, and radio waves. These divisions, although useful in practice, are the results of the quirks of history.

Light can be produced in many ways. Consider lighting a candle. The candle flame produces a continuous spectrum, emitted primarily by the soot particles within the flame. The temperature of a typical candle flame is about 700 Kelvin, but its color is much yellower than a blackbody at that

[1] I will use "electromagnetic radiation" and "light" interchangeably; when I want to speak specifically about those wavelengths that our eyes can detect, I'll use the phrase "visible light".

temperature.[2] This color anomaly results from the fact that the soot particles are generally less than a micron across, and are very inefficient at making light with a wavelength of more than one micron. The light energy is thus carried away by light with wavelengths of less than a micron; much of the light lies in the visible range of the spectrum ($400\,\mathrm{nm} < \lambda < 750\,\mathrm{nm}$). The moral of the candle's story is that thermal radiation is not necessarily blackbody radiation.

From the classical viewpoint, electromagnetic radiation can be created by accelerating a charged particle. In practice, it is easily to accelerate an electron than a proton, so most continuum radiation processes of astrophysical interest involve accelerating electrons.

One way of accelerating electrons is to raise their temperature, and produce *thermal radiation*. For instance, an opaque body produces *blackbody radiation* when it is heated. (Although, as we saw while examining hot soot, the opaque body can't produce wavelengths much longer than itself.) As shown in Figure 1, stars similar to the Sun have a spectrum that is

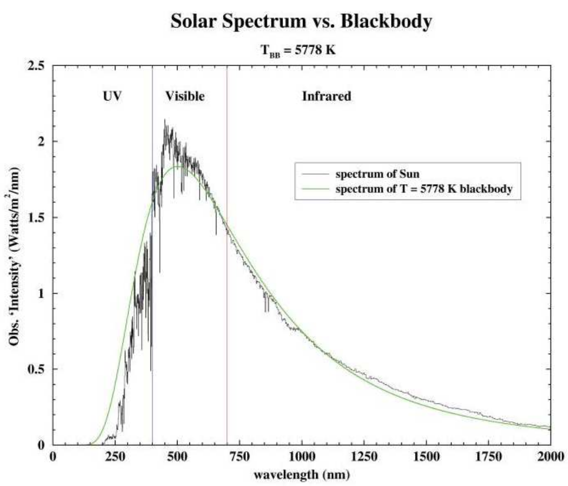

Figure 1: (Approximate) blackbody spectrum: the Sun

fairly well approximated by a blackbody. A transparent cloud of ionized gas, when it is heated, will produce a *bremsstrahlung* spectrum. The word "bremsstrahlung" is the German term for "braking radiation", and refers to the radiation produced when an electron is accelerated by its interaction with

[2] We'll discuss blackbodies in more detail next week.

another charged particle. Bremsstrahlung radiation is seen from HII regions

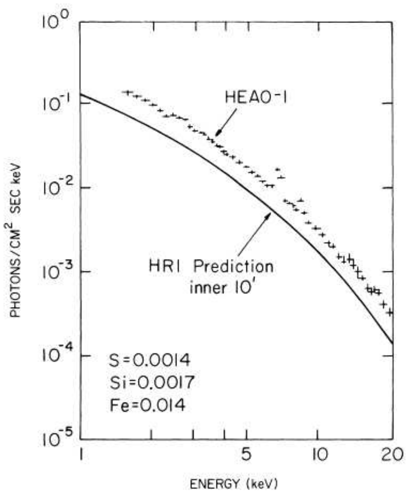

Figure 2: Bremsstrahlung spectrum: the Orion nebula

such as the Orion nebula (Figure 2).

Electrons can also be accelerated by their interactions with *magnetic fields*. For instance, when non-relativistic electrons encounter a uniform magnetic field of strength B, they are accelerated on orbits with frequency $\omega = eB/(m_e c)$. The radiation produced by these circling electrons is called *cyclotron radiation*. Cyclotron spectra are produced by magnetic cataclysmic variables such as VV Puppis (Figure 3).[3] Cyclotron spectra often show broad humps at harmonics of the fundamental cyclotron frequency ω. When *relativistic* electrons are accelerated by a magnetic field, the resulting light is called *synchrotron radiation*. Young supernova remnants such as the Crab nebula (Figure 4) contain both hot gas and strong magnetic fields, and thus produce synchrotron radiation.

[3]A magnetic cataclysmic variable is a highly magnetized white dwarf onto which gas is being dumped by a companion star.

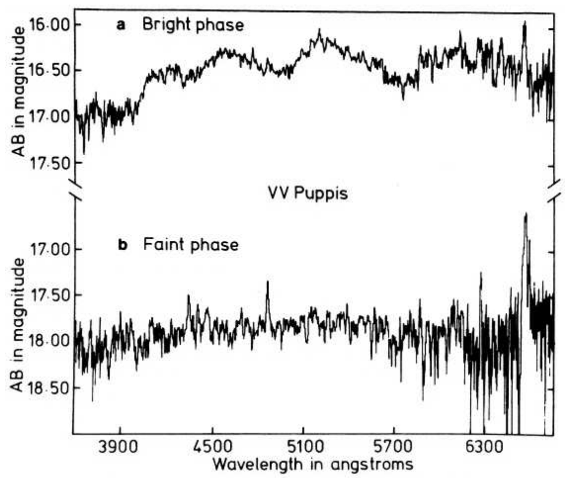

Figure 3: Cyclotron spectrum: VV Puppis

2 Friday, September 23: Photon - Electron Interactions

Once light is created, by whatever process, it *radiates* away from its source.[4] As long as light travels through a vacuum in Euclidean space, it travels along a straight line. However, encounters with matter can modify the path of an electron, as well as changing its energy.[5]

Photons can be scattered by encounters with charged particles (in practice, usually electrons). Physicists find it useful to distinguish between three types of scattering: Thomson scattering, Compton scattering, and inverse Compton scattering.

Thomson scattering (named after J. J. Thomson, discoverer of the electron) is the scattering of a low energy photon from an electron: $h\nu \ll m_e c^2$ in the rest frame of the electron. In this limit, light can be thought of as an electromagnetic wave which causes the electron to oscillate with a frequency ν. The oscillating electron then re-radiates light at the same frequency ν. Thus, Thomson scattering doesn't significantly affect the frequency of light.

[4]The terms "radiate", "radiation", and "ray" all have their origin in the Latin word "radius", which originally referred to the spoke of a wheel.

[5]If space is not Euclidean, the geodesics along which light travels will not necessarily be straight lines. However, in this course I'll assume that space is Euclidean and static unless explicitly stated otherwise.

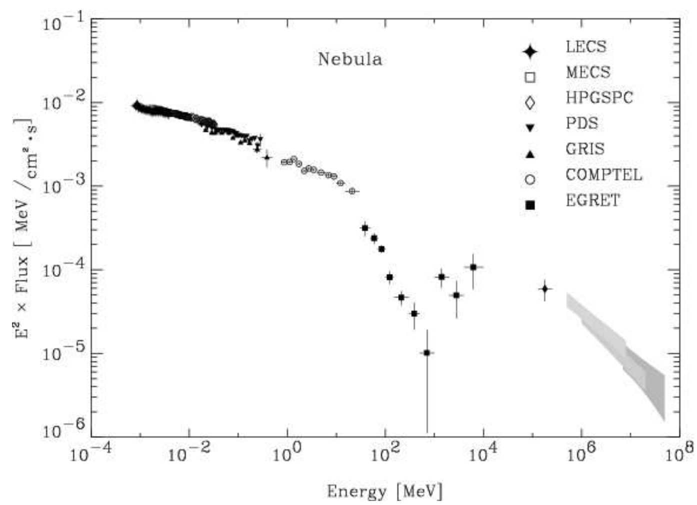

Figure 4: Synchrotron spectrum: the Crab nebula

Compton scattering (named after Arthur Holly Compton) is the scattering of a high energy photon from an electron: $h\nu \gg m_e c^2 \approx 0.5\,\mathrm{MeV}$ in the rest frame of the electron. In this limit, the gamma-ray light can be thought of as a stream of high-energy particles. When a gamma-ray photon strikes an electron (Figure 5), some of the photon's energy is transfered to the electron

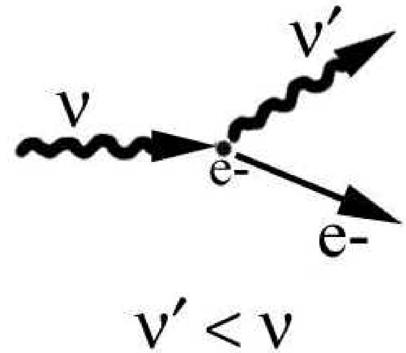

Figure 5: Compton scattering – photon loses energy

with which it collides. (It's a "billiard ball" collision in which momentum and energy are conserved.) Compton scattering is an important concept in gamma-ray physics, since it is the main mechanism by which photons in the energy range $1\,\mathrm{MeV} < E < 30\,\mathrm{MeV}$ lose energy as they travel.[6]

Thomson scattering leaves the photon energy almost unchanged ($\nu \approx$ constant). Compton scattering decreases the photon energy (ν decreases). Scattering that increases the photon energy (ν increases) is referred to as *inverse Compton scattering*. If the photon is to gain energy, then the electron with which it collides must have an initial kinetic energy greater than the photon's initial energy: $h\nu \ll m_e v_e^2/2$ in the observer's frame of reference. In this limit, a fast-moving electron collides with a low-energy photon (Figure 6) and some of the electron's kinetic energy is transfered to the photon with

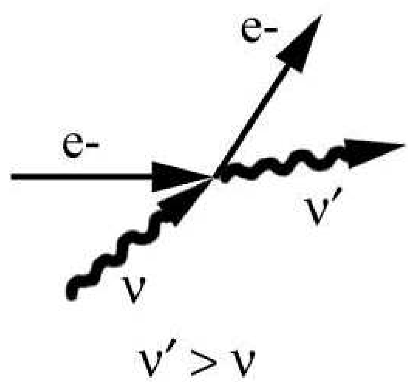

Figure 6: Inverse Compton scattering – photon gains energy

which it collides. Since the universe is full of photons (over one billion photons per electron), the inverse Compton effect is a major cooling mechanism for hot plasmas. The Sunyaev-Zeldovich effect is just one manifestation of inverse Compton scattering. In the S-Z effect, cosmic microwave background photons pass through the hot intracluster gas in a rich cluster of galaxies; the inverse Compton effect scatters some of the photons to higher energies, distorting the shape of the cosmic microwave background spectrum.

Here ends the overview of Electromagnetic Radiation. When charged particles are accelerated, they produce photons. These photons can later interact with other charged particles and increase their energy, decrease their energy, or change their direction of motion. The rest of the course will be applications of these principles.

To study in detail how light is generated and how it propagates through a medium, we need to define, with precision, a few important terms. One

[6] Higher energy gamma-rays lose energy mostly by electron/positron pair production.

important idea is that of *energy flux*, usually designated by the symbol F. Consider a tiny transparent window of area dA. The net amount of energy carried by photons through the window area dA in a short time dt is

$$dE = F dt dA \ , \tag{3}$$

where F is the energy flux, which has units of $\mathrm{erg\,s^{-1}\,cm^{-2}}$ in cgs units. The flux through the window depends, in general, on its orientation as well as its location relative to all the light sources in the universe.

The energy flux F consists of contributions from photons of all wavelengths coming from all points on the sky. Usually, we astronomers are more discriminating; we want to know how much energy is arriving in a particular range of frequencies from a particular small patch of sky (soft X-rays from the Crab nebula, for instance, or two-micron radiation from Proxima Centauri). Thus, we need another function, called the *specific intensity* (or sometimes the brightness), which takes into account the frequency and direction of origin of photons. The specific intensity is defined by setting up, once again, our little transparent window of area dA. We draw a ray which is perpendicular to the surface of the window.[7] We select a small solid angle $d\Omega$ around the point on the celestial sphere at which the ray is pointing. We then ask how much energy passes through our window during a time dt, carried by photons from the solid angle $d\Omega$ with frequencies in the range $\nu \to \nu + d\nu$. The answer is

$$dE = I_\nu dt dA d\Omega d\nu \ , \tag{4}$$

where I_ν is the specific intensity at frequency ν. In cgs units, the specific intensity has units of $\mathrm{erg\,s^{-1}\,cm^{-1}\,steradian^{-1}\,Hz^{-1}}$. As an example, Figure 7 shows the specific intensity of a point on the sky in the frequency range $0.5\,\mathrm{GHz} < \nu < 1000\,\mathrm{GHz}$. This shows the Cosmic Microwave Background (CMB), which is the dominant source of radiation at these microwave frequencies, as long as your little window is above the Earth's atmosphere, and is pointed away from the plane of our galaxy (which produces significant synchrotron radiation at the low-frequency end of this interval).

The net flux in the frequency interval $\nu \to \nu + d\nu$ is related to the specific intensity by the relation

$$F_\nu = \int I_\nu \cos\theta d\Omega = \int \int I_\nu \cos\theta d(\cos\theta) d\phi \ . \tag{5}$$

[7]If we set the window flat on the Earth's surface, for instance, the ray would point to the zenith, directly overhead.

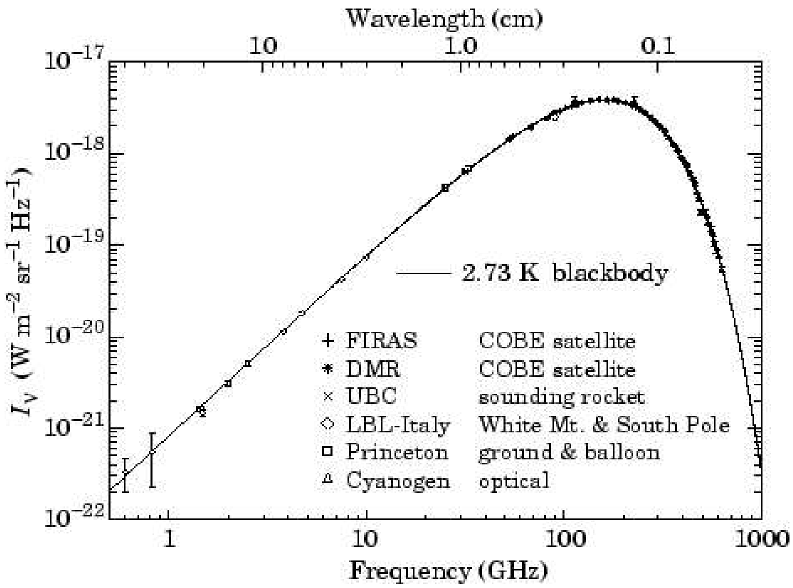

Figure 7: Specific intensity of the Cosmic Microwave Background

(I recommend examining figure 1.3 of the textbook if you don't immediately see where the factor of $\cos\theta$ comes from.) The total energy flux over all frequencies is then

$$F = \int_0^\infty F_\nu d\nu \ . \tag{6}$$

The text also shows how to find the momentum flux through the window:

$$p_\nu = \frac{1}{c} \int I_\nu \cos^2\theta d\Omega \ , \tag{7}$$

and the energy density of photons:

$$u_\nu = \frac{1}{c} \int I_\nu d\Omega \ . \tag{8}$$