3. Electromagnetic Radiation, Redshift, and the Expanding Universe

Reading: The reading for this section is still covered by reading assignment 1, chapters 1-3.

The Speed of Light

The large but finite speed of light was first measured by Ole Roemer in 1676, based on the timing of eclipses of Jupiter's moon Io. These appeared to be delayed when Jupiter was further from the earth, and Roemer correctly identified the cause of the delay as the time required for light to travel the longer distance to earth.

It has since been measured extremely accurately, using both astronomical observations and laboratory experiments.

In empty space, the speed of light is

$$c = 300,000\,\mathrm{km/sec} \quad = 3 \times 10^8\,\mathrm{meters/sec} \quad = 1\,\mathrm{light-year/year}.$$

(Today we have measured c to many more decimal places, $c = 299,792,458$ m/s.)

A light-year is the distance light travels in one year (3.16×10^7 sec).

In English units, c is 186,000 miles/sec. It is also, approximately, 1 foot per nano-second; in a billionth of a second, light goes one foot.

Thanks largely to Albert Einstein, we now understand c to be a universal number, constant throughout time and space, and an upper limit to the speed that any object can possibly travel.

Light travels more slowly through a transparent medium such as water or glass.

Electromagnetic Radiation

What is light anwyay?

In the 1860s, James Maxwell postulated the existence of electromagnetic (EM) radiation: waves of electric and magnetic fields that propagate through space.

Existence first clearly demonstrated in the 1880s by Heinrich Hertz, who in effect built the first radio.

In empty space, all EM radiation propagates at the speed of light.

Different forms of EM radiation are distinguished by their wavelength, or by their frequency.

Visible light is a form of electromagnetic radiation with wavelength of about 500 nano-meters (nm, 1 nm = 10^{-9} meters).

The wavelength of light determines its color.

From long wavelength to short wavelength:

- Radio and microwave (greater than 10^6 nm = 1 mm)
- Infrared ($\sim 10^6\,\mathrm{nm} - 10^3\,\mathrm{nm}$)
- Visible: R O Y G B I V ($\sim 700\,\mathrm{nm} - 400\,\mathrm{nm}$)
- Ultraviolet ($\sim 100\,\mathrm{nm} - 10\,\mathrm{nm}$)
- X-rays ($\sim 10\,\mathrm{nm} - 0.01\,\mathrm{nm}$)
- Gamma rays (less than $\sim 0.01\,\mathrm{nm}$)

Astronomers usually refer to the range 300-1000 nm as "optical" light.

EM radiation carries energy, e.g., sunlight heats the Earth, microwaves can cook food.

EM radiation also carries momentum, e.g., if light bounces off a mirror, the mirror recoils.

Photons

EM radiation has many wavelike properties — refraction, interference.

In early 20th century, Planck and Einstein showed that it travels in discrete packets of energy, now known as *photons.*

Photons can be thought of as "particles of light."

It's counter-intuitive for something to be both particle and wave, but that's the way nature is.

The energy of a photon is

$$E = \frac{hc}{\lambda}$$

E = energy of photon
λ = wavelength of photon
c = speed of light
h = Planck's constant (a universal number)

An individual short wavelength photon has *more energy* than an individual long wavelength photon.

Radio photon: not much energy.

X-ray or Gamma-ray photon: lots of energy.

What A Telescope Does

A telescope does two main things: it collects lots of light, and it magnifies.

Collecting more light allows you to detect fainter objects, or to measure brighter objects more accurately.

Magnification allows you to see detail in extended objects.

For the purposes of astronomy, it is the light gathering ability of telescopes that is more important, and more fundamental.

The light gathering power of a telescope is determined by the area of its primary mirror (or, in some cases, lens).

The magnification is determined by additional optics and detectors after the primary, and these can be changed.

A telescope with a larger primary mirror telescope can make sharper images, allowing higher maximum magnification, but for ground-based astronomy the limit on resolution is usually set by blurring from the atmosphere rather than the size of the telescope.

Space telescopes are above the atmosphere, so their resolution is usually limited by the size of the primary mirror.

The biggest optical telescopes today are the Keck telescopes in Hawaii, with mirrors that are 10-meters in diameter, and the Large Binocular Telescope (LBT) in Arizona, which has two 8.4-meter diameter mirrors on a single mount. (Ohio State has a 1/6 share of the LBT.)

Hubble Space Telescope has a 2.4-meter primary mirror. This is almost the same size as the (ground-based) telescope that Edwin Hubble used to discover Cepheids in Andromeda.

The scientific power of a telescope also depends strongly on the instruments (cameras, spectrographs) that it has. Big telescopes are great for studying faint objects, but smaller telescopes equipped with good instruments can also be very powerful.

Compared to the naked eye, a well equipped telescope can see much, much fainter because (a) it collects light over the area of the primary mirror, not the area of the pupil of the eye, (b) it can add light up over time, e.g., with a one-hour exposure of a camera, and (c) good electronic detectors are more efficient at capturing photons than the eye is.

The most familiar telescopes are those designed for optical light.

Since the mid-20th century, astronomers have also developed telescopes for other forms of EM radiation: radio telescopes, infrared telescopes, ultraviolet telescopes, X-ray telescopes, and gamma-ray telescopes.

Ultraviolet, X-ray, and gamma-ray radiation, and some wavelengths of infrared radiation, cannot penetrate the earth's atmosphere, so they can only be observed from space.

The *James Webb Space Telescope*, which is planned for launch in 2018 and is intended as the successor to Hubble Space Telescope, is an infrared telescope with a 6.5-meter primary mirror.

Doppler Shift

Doppler shift: EM radiation of wavelength λ received from an object moving away at velocity v is shifted to a longer wavelength:

$$\lambda_o = \lambda_e \times \left(1 + \frac{v}{c}\right).$$

λ_o = observed wavelength
λ_e = emitted wavelength
v = velocity of emitting object away from the observer
c = speed of light.

This is called a redshift, since the shift is to longer, "redder" (in the case of visible light) wavelengths.

Note that while "speed" refers to how fast something is moving, "velocity" also refers to the direction.

An object moving at 1000 m/s towards you has a different velocity from an object moving at 1000 m/s away from you, or 1000 m/s side-to-side.

In the above formula, the velocity of something moving towards you would be negative.

Thus, if the object is moving towards you at velocity v, the radiation is shifted to shorter wavelength. This is a blueshift.

The Doppler phenomenon is straightforward to understand, and it affects all sorts of waves, including sound waves, ocean waves, etc. (See Figure 2.27 in the textbook.)

Side-to-side motion does not produce a Doppler shift. (This statement is not exactly accurate, but it is accurate enough for our purposes.)

The book gives an equivalent equation (equation 2.3) for the *shift* in wavelength, $\Delta\lambda = \lambda_o - \lambda_e$:

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}.$$

What can we measure from an astronomical object?

If we observe an astronomical object through a telescope, we can measure:

- Apparent brightness. If we also know the distance, then we know the *intrinsic* brightness, how much energy the object is putting out.
- Motion on the sky. Nearby stars change position slightly as they move through space and as the earth goes around the sun. Limited to stars that are close or moving fast.
- Variability. Some stars (and some other objects) get brighter and fainter, irregularly or periodically. We can learn something from how they vary. Limited to variable objects.
- Color. For stars, this tells us about the temperature of the surface. Hotter stars put out more blue light (more energetic, shorter wavelength photons).

We get the most information about an object (unresolved or resolved) if we spread out its light by passing it through a prism (or a similar device that sends red and blue light in different directions) to measure its *spectrum*.

Information From Spectra

The spectrum of an object is a plot of the intensity of its light against wavelength.

In addition to showing the overall amount of blue vs. red light, spectra show patterns of "missing" light or "extra" light at very specific wavelengths.

These are produced by atoms, which like to absorb or emit light at specific wavelengths.

These wavelengths can be measured in laboratory experiments, so we know (in many cases) what absorption or emission lines correspond to what atoms.

The spectrum of an object can tell us about:

- What kinds of atoms are present.
- The temperature and density of the gas, which determines which atoms will be emitting or absorbing light.
- The velocity of the object along the line of sight (towards us or away from us), from the Doppler shift.

We will care about all of these, but for the moment we are especially interested in the ability to measure Doppler shift, even when the velocity of the object is much smaller than the speed of light.

The Discovery of the Expanding Universe

1921: Using the 100" telescope, Edwin Hubble demonstrates that "spiral nebulae" are galaxies, giant stellar systems like the Milky Way, and are therefore at great distances.

1920s: Vesto Slipher and others measure spectra, and thereby Doppler shifts, of galaxies. Most are redshifted. Hubble uses apparent brightness of luminous stars to estimate distances of galaxies.

1920s: The theoretical physicists Alexander Friedmann and Georges Lemaître, using Einstein's newly developed theory of gravity (called General Relativity), develop theoretical models in which the universe expands or contracts.

1929: Hubble uses measured distances and velocities to announce discovery of the "velocity-distance relation."

Hubble's 1929 plot. What does it show?

According to Hubble: a galaxy's recession velocity is proportional to its distance.

Hubble's 1935 data. More convincing. He now uses the apparent brightness of entire galaxies as a "standard candle," which allows him to go 10 times further away than he could in 1929, using only the brightest stars

Hubble's comment: "Red-shifts resemble velocity-shifts, and no other satisfactory explanation is available at the present time: red-shifts are due either to actual motion of recession or to some hitherto unrecognized principle of physics. Therefore, the empirical law is generally described as the *velocity-distance relation* (velocity = constant × distance), and is often considered as visible evidence of the expanding universe of general relativity."