Newton's laws of motion and gravity

1. Every body continues in a state of rest or uniform motion (constant velocity) in a straight line unless acted on by a *force*.
(A deeper statement of this law is that momentum (mass x velocity) is a conserved quantity in our world, for unknown reasons.)
This tendency to keep moving or keep still is called "inertia." (Nobody really knows what it means.)

2. *Acceleration* (change in speed or direction) of object is proportional to: applied force F divided by the mass of the object m

i.e. $a = F/m$ or (more usual) $F = ma$

This law allows you to calculate the motion of an object, if you know the force acting on it. This is how we calculate the motions of objects in physics and astronomy.

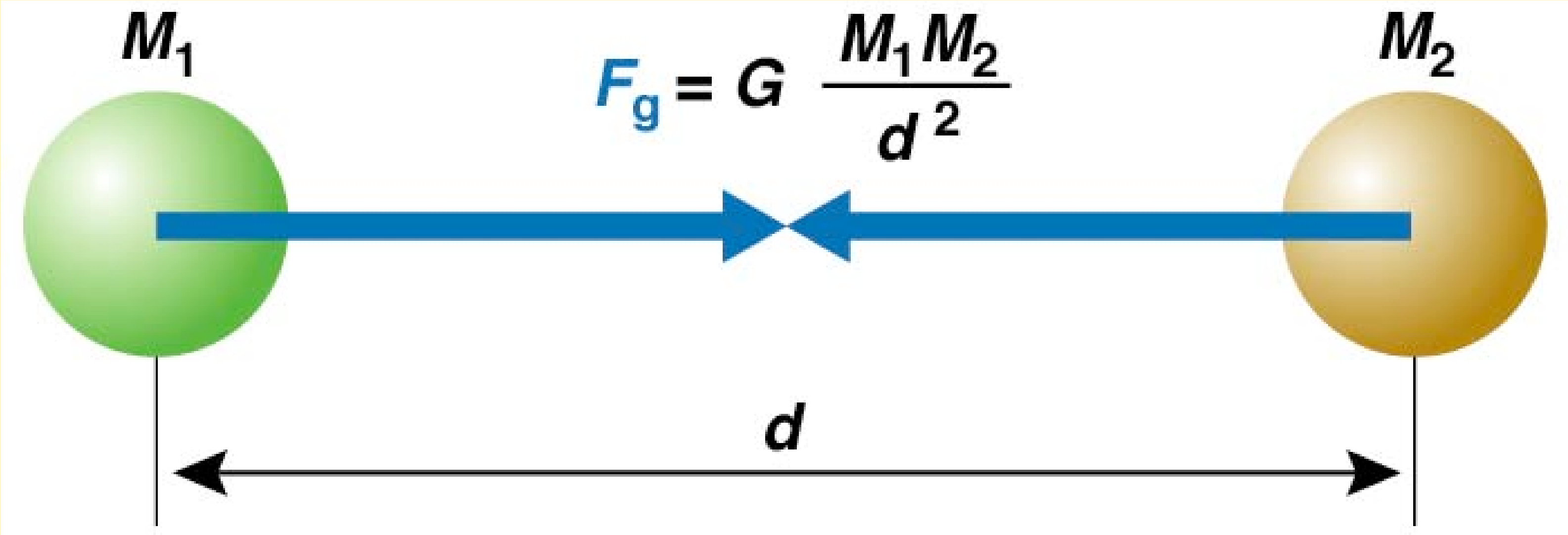
You can see that if you know the mass of something, and the force that is acting on it, you can calculate its *rate of change of velocity*, so you can find its velocity, and hence position, as a function of time.

3. To every action, there is an equal and opposite reaction, i.e. forces are mutual. A more useful equivalent statement is that interacting objects exchange momentum through equal and opposite forces.

What determines the strength of gravity?

The **Universal Law of Gravitation:**

1. Every mass attracts every other mass.
2. Attraction is *directly* proportional to the product of their masses.
3. Attraction is *inversely* proportional to the *square* of the distance between their centers.



Newton's Law of Gravity: **Every object attracts every other object with a force**

➡ F (gravity) = (mass 1) x (mass 2) / R^2 (distance squared)

Notice this is an "inverse square law"(left illus. below).

Orbits of planets (and everything else) are a balance between the moving object's tendency to move in a straight line at constant speed (Newton's 1st law) and the gravitational pull of the other object (right illus.). Now we'll see how all this can be combined to calculate the motion of any object moving under any force (gravity or otherwise--like a magnetic force, or friction, or anything.

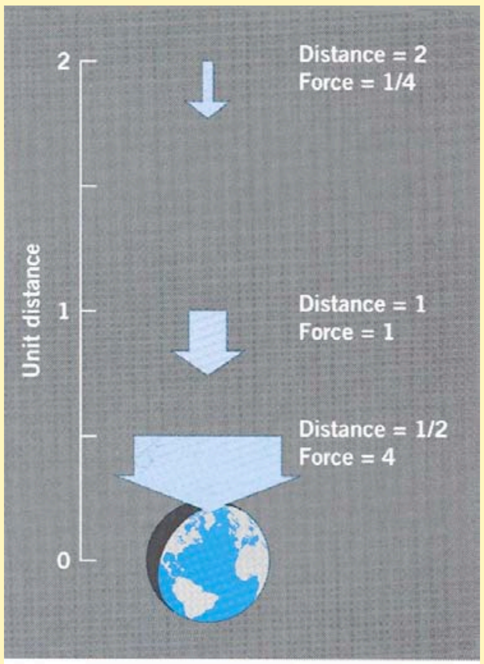
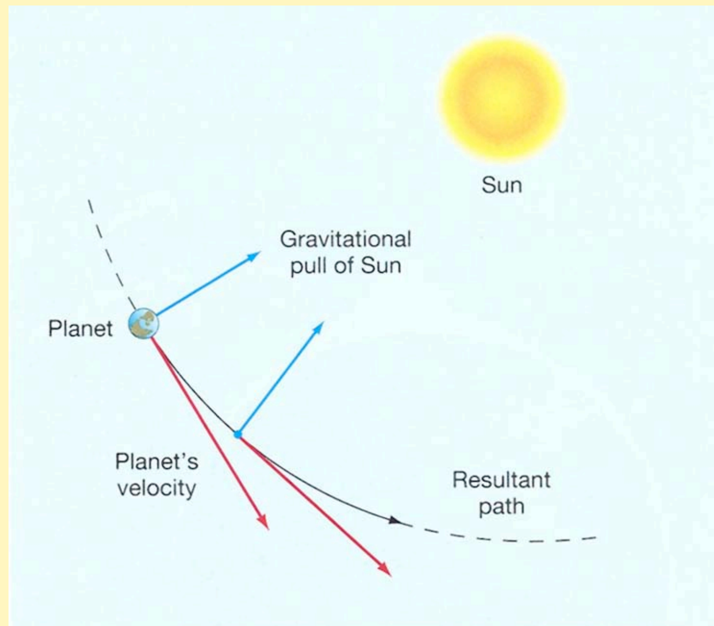


FIGURE 4.17 Moving the same mass at three different relative distances from the earth. For each distance, the thickness of the arrow indicates the relative amount of the gravitational force between the mass and the earth.



▲ FIGURE 2.24 Solar Gravity The Sun's inward pull of gravity on a planet competes with the planet's tendency to continue moving in a straight line. These two effects combine, causing the planet to move smoothly along an intermediate path, which continually "falls around" the Sun. This unending "tug-of-war" between the Sun's gravity and the planet's inertia results in a stable orbit.

More on the Newton's law of gravity

How is this "force" transmitted instantaneously, at a distance? ("Gravitons"--translation: we don't know). Today, gravity interpreted as a "field" that is a property of space-time itself, or even stranger interpretations…

But for almost all applications, Newton's law of gravity is sufficient for us to calculate the orbits of nearly all astronomical objects. We only need to combine it with Newton's 2nd law ($a = F/m$, where F is the expression for the force of gravity); then we can solve for the acceleration, which is the change of velocity with time. This gives us the velocity (you have to solve a "differential equation" $a = dv/dt = \ldots$) and position of the object as a function of time.

From this you (or at least someone) can derive Kepler's laws from Newton's laws of motion and the form of the gravitational force. The result for Kepler's third law contains a new term:

$$P^2 = a^3 / (m_1 + m_2)$$ → Newton's form of Kepler's 3rd law.

(Masses expressed in units of solar masses; period in years, a in AU, as before).

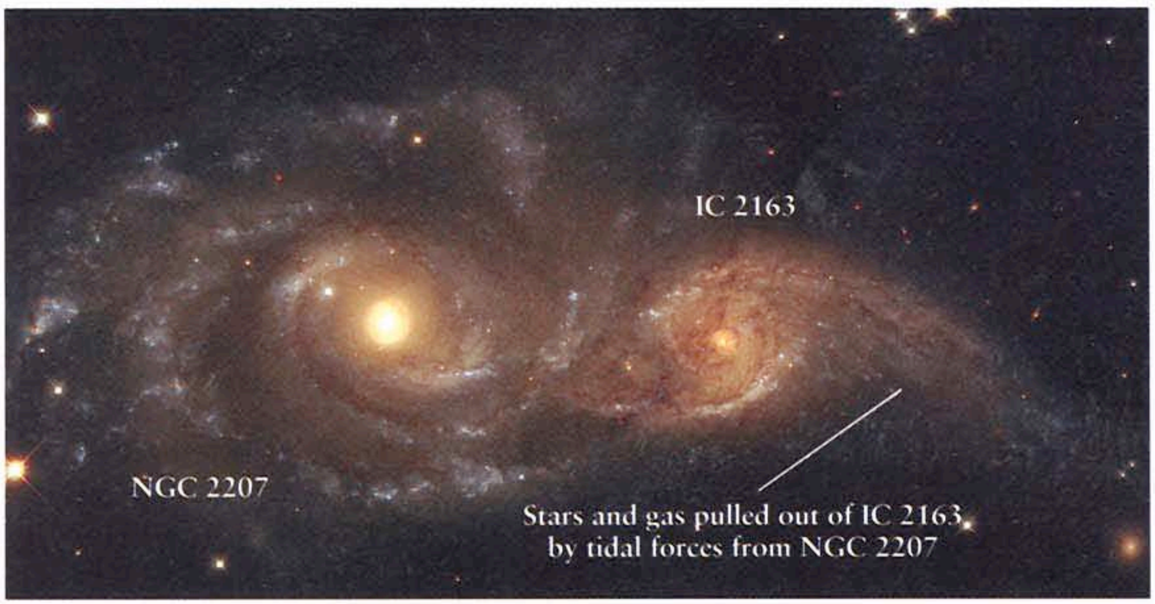
This is basically what is used (in various forms) to get masses of ALL cosmic objects! Another way to word it: if you know how fast two objects are orbiting each other, and their separation (notice you need the distance to get this), you can solve for the sum of their masses.

But the most important application is that the motion of *any* object (or number of objects) acting under *any force* can be calculated, in principle, *if the force can be specified* (e.g. gravitational force as a function of mass and distance)

Examples:

- Earth's orbital period (1 year) and average distance (1 AU) tell us the Sun's mass.
- Orbital period and distance of a satellite from Earth tell us Earth's mass.
- Orbital period and distance of a moon of Jupiter tell us Jupiter's mass.
- Motion of stars in galaxies reveals the existence of invisible mass, or "dark matter," whose nature remains unknown.

Illustration below shows effect of gravitational forces between two galaxies that are in the early stages of merging. Solving Newton's laws for millions of stars and for the gas within these galaxies, we can actually make models for such phenomena that show what is going on (tidal forces in this case). This example shows you that some orbits can decay, leading to merging of objects. We will see this again when we discuss the cannibalism of planets by their parent stars.



WEB LINK 4.10

figure 4-26 R I V U X G

Tidal Forces on a Galaxy For millions of years the galaxies NGC 2207 and IC 2163 have been moving ponderously past each other. The larger galaxy's tremendous tidal forces have drawn a streamer of material a hundred thousand light-years long out of IC 2163. If you lived on a planet orbiting a star within this streamer, you would have a magnificent view of both galaxies. NGC 2207 and IC 2163 are respectively 143,000 light-years and 101,000 light-years in diameter. Both galaxies are 114 million light-years away in the constellation Canis Major. (NASA and the Hubble Heritage Team, AURA/STScI)

New topic: **Properties of Light** (ch. 3 in text)

This is an extremely important topic, because the only thing we can learn about things outside our solar system is by analyzing the light they send us. In a sense astronomy is all about how to collect, analyze, and interpret light.

Can consider light as waves or as particles, depending on circumstance. (One of the "big mysteries" of physics.) Either way, it is common practice to call them "photons."

Light can be thought of as a wave that arises due to an oscillating (vibrating) electromagnetic field (see text). Unlike other kinds of waves, light does not require a material medium for its propagation (travel); light can propagate in a vacuum.

(Don't worry about "polarization" in text if it is confusing to you.)

Waves: Need to understand and become familiar with the following properties of light (will discuss in class):

Wavelength—Always denoted by Greek letter "λ".

Frequency—how many waves pass per second, denoted "f"

Speed—All light waves travel at the same speed, the "speed of light", "c"(=$3x10^5$ km/sec = $2.86x10^5$ mi/sec (286,000 miles per second); no need to memorize these numbers!)

Energy--the energy of a photon is its frequency times its speed E = f x c

It is extremely important that students become familiar and comfortable with these terms and symbols--they will recur throughout the class.

The fact that light travels at a finite speed ("c") means that we see distant objects as they were in the past. Consider our neighbor, the Andromeda galaxy shown in Fig. 3.1 in your text—it is about 2 million light years away… Later we will "look back" to times near the beginning of the universe (billions of years ago) using very distant galaxies.

Spectrum: → Possibly the most important term to understand in this course! It refers to the mixture of light of different wavelengths from a given source; best to remember it as a graph of "intensity" (or brightness) of radiation in each wavelength (or frequency) interval. Will discuss in class.

(Note: much of rest of class is concerned with analyzing the spectra of different types of astronomical objects—so *get used to the concept now*.)

Light from all objects covers an extremely large range of wavelengths (or frequencies), from radio waves to gamma rays. Memorize this list, and study figs. 3.4 and 3.9 carefully:

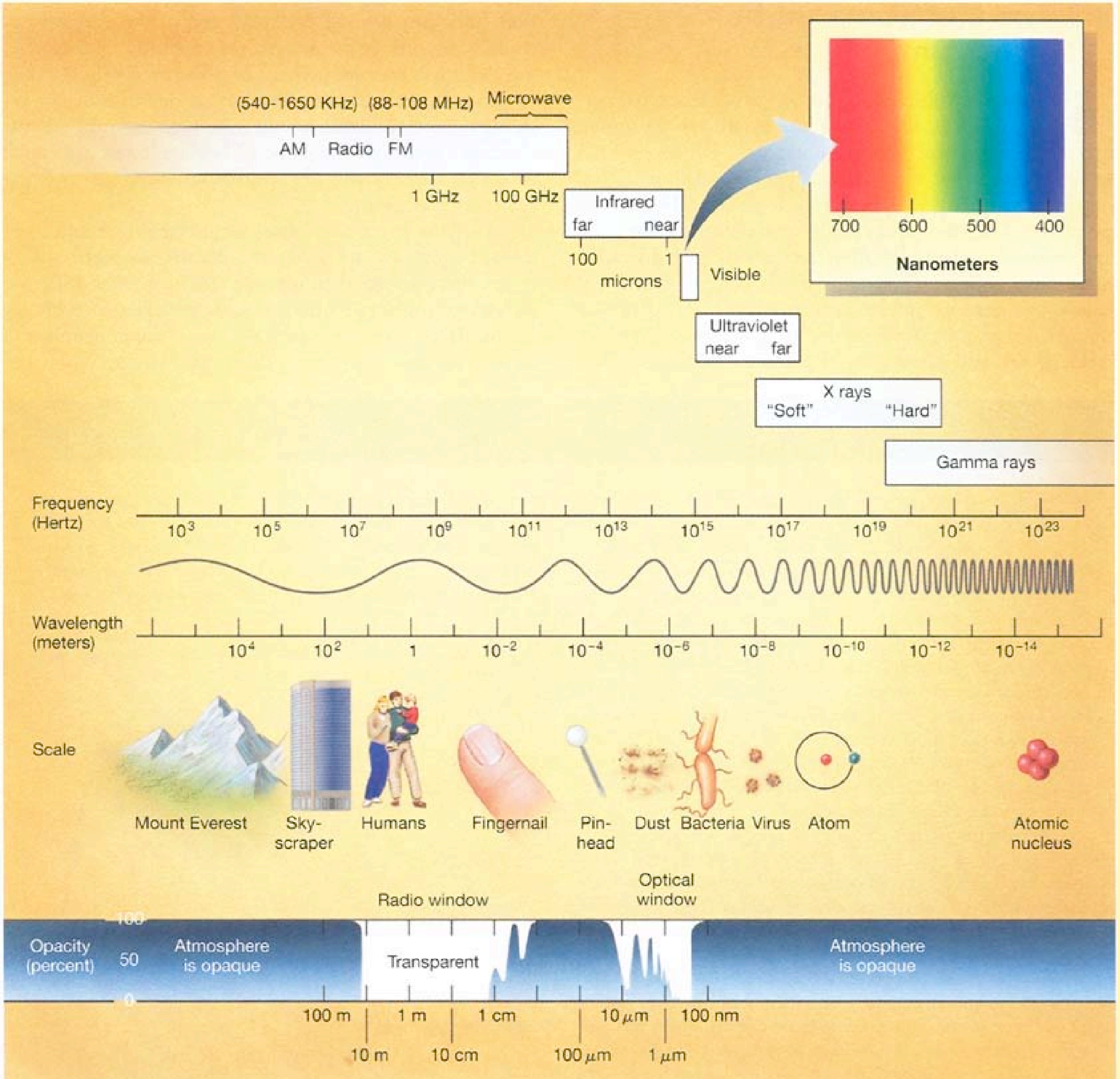
radio, infrared (IR), visible, ultraviolet (UV), x-rays, gamma rays

It lists the regions of electromagnetic spectrum, i.e. the classes of light, from smallest frequency (largest wavelength) to largest frequency (smallest wavelength). It also goes from smallest energy to highest energy.

Human vision is only sensitive to a very tiny fraction of all this radiation—astronomy in the last 50 years has been mostly concerned with getting out of this region.

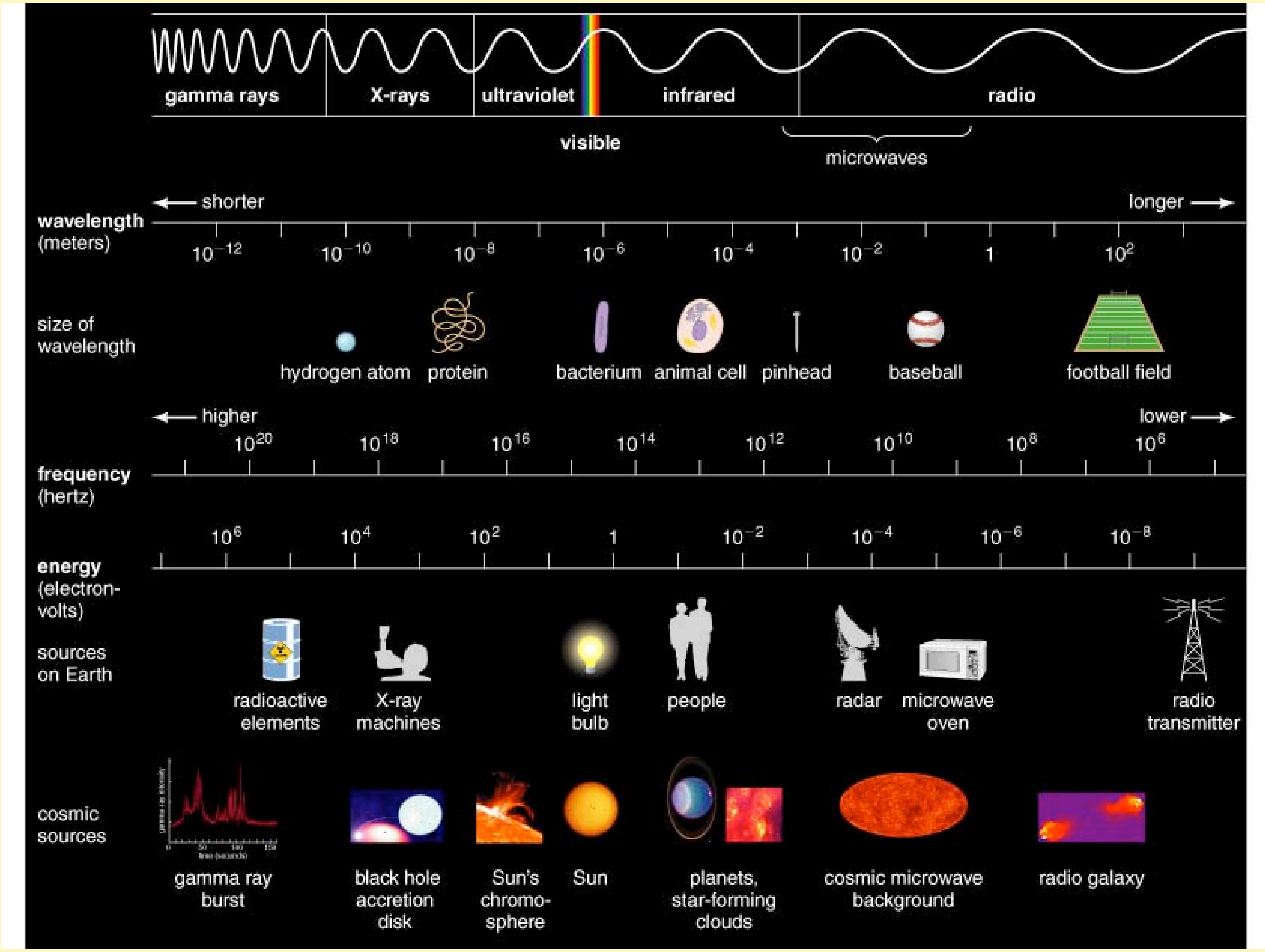
The illustration (from your text) on the next slide illustrates the different categories of light--please note that they are just historical conventions that are useful. But there is no definite “boundary” between, say, ultraviolet and x-rays, or infrared and radio.

The units of wavelength (e.g. Angstroms, nanometers, microns) and frequency (Hertz, MHz, GHz) are just something you have to get used to in order to understand the text and the lectures, but you will not be asked to manipulate or memorize them on exams. However do not ignore them either, or you’ll have much trouble reading the text or understanding lectures.



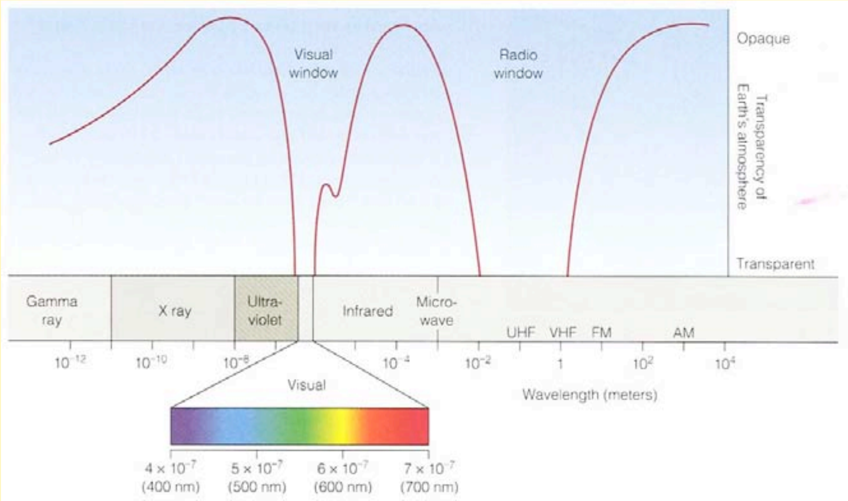
▲ **FIGURE 3.9 Electromagnetic Spectrum** The entire electromagnetic spectrum, running from long-wavelength, low-frequency radio waves to short-wavelength, high-frequency gamma rays.

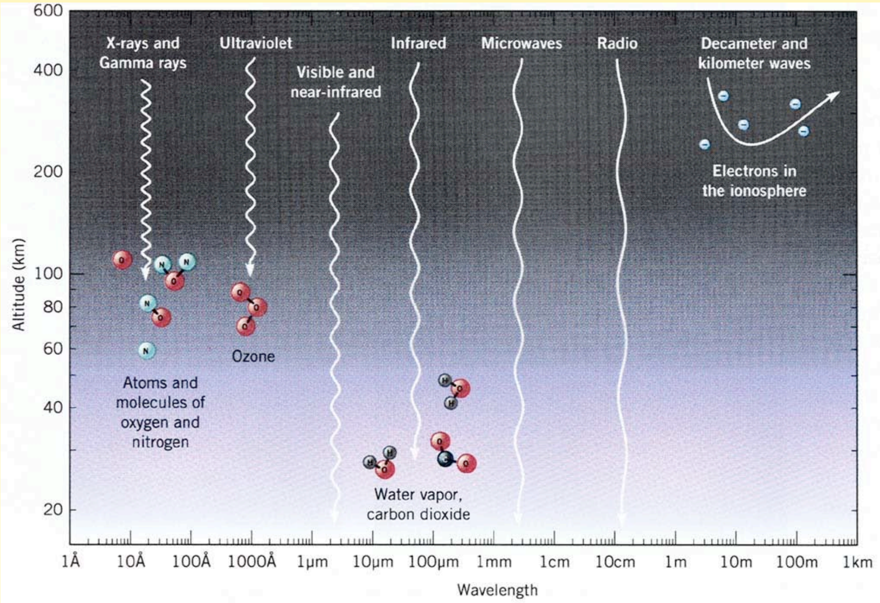
The electromagnetic spectrum again



Atmospheric absorption and "windows"

Earth's atmosphere is very opaque (light can't get through) except in the visible (also called "optical") and radio parts of the spectrum (the so-called optical and radio "windows")
That's why much of recent astronomy is done from satellites





Black-Body Spectrum

A "black-body" (BB) is only a simplified mathematical model, but works surprisingly well for the continuous (smooth) spectra of objects.

Gives **spectrum** (intensity vs. wavelength or frequency--be sure you understand this word!) for any temperature.

Two ways in which a BB can be related to temperature:

1. **Wien's law**: relates wavelength at which most energy is emitted in the spectrum ("wavelength of peak emission") to the temperature:

$$\lambda_{max} \propto 1/(\text{temperature of object})$$

So hotter object → bluer, cooler object → redder. You'll be surprised how often this simple result is used in astronomy.

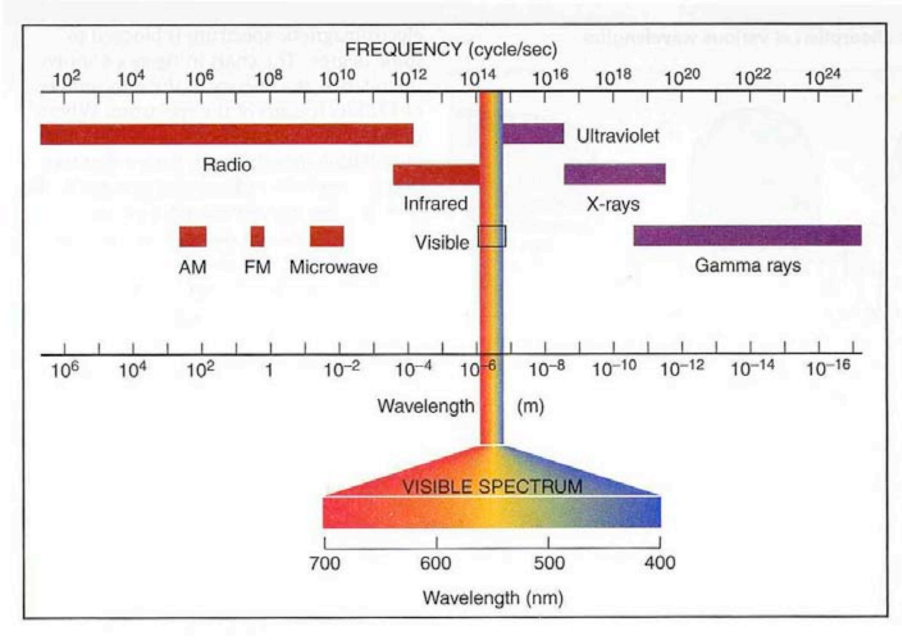
So we can get temperature from the spectrum. (See fig.3.11 in text)

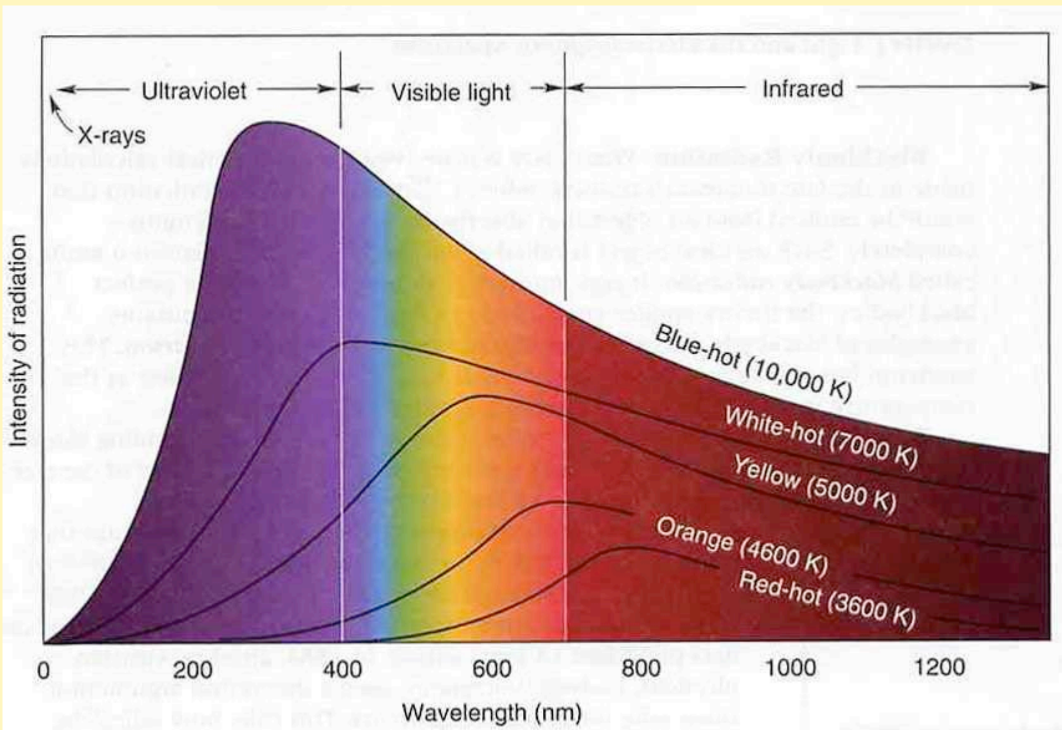
2. **Stefan's law**: TOTAL energy E radiated at *all* wavelengths (*per unit surface area*, meaning per square inch, or per square meter, or per square anything) is related to the temperature by:

$E \propto (\text{temperature})^4$ → hotter objects will be brighter (per unit area)

Notice the steep temperature dependence!

Make something a little hotter and it will become much brighter! (If it behaves like a BB.) Study Fig. 3.13 (BB curves for 4 cosmic objects).





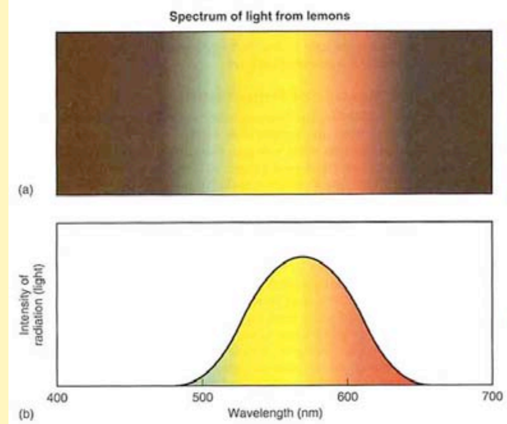


Figure 4-7
(a) If light reflected from the lemons were sent through a prism to reveal its spectrum, we would see that the lemons reflect mostly yellow light.
(b) This graph indicates the relative intensity of the various wavelengths of light from the lemons.

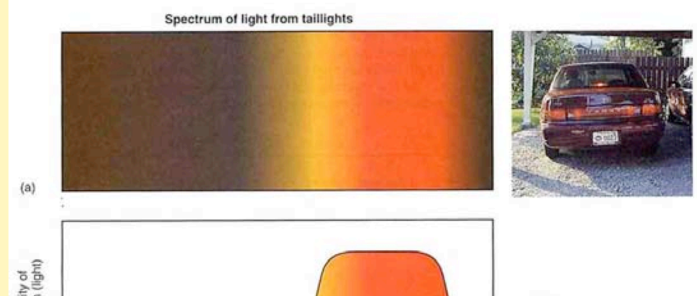
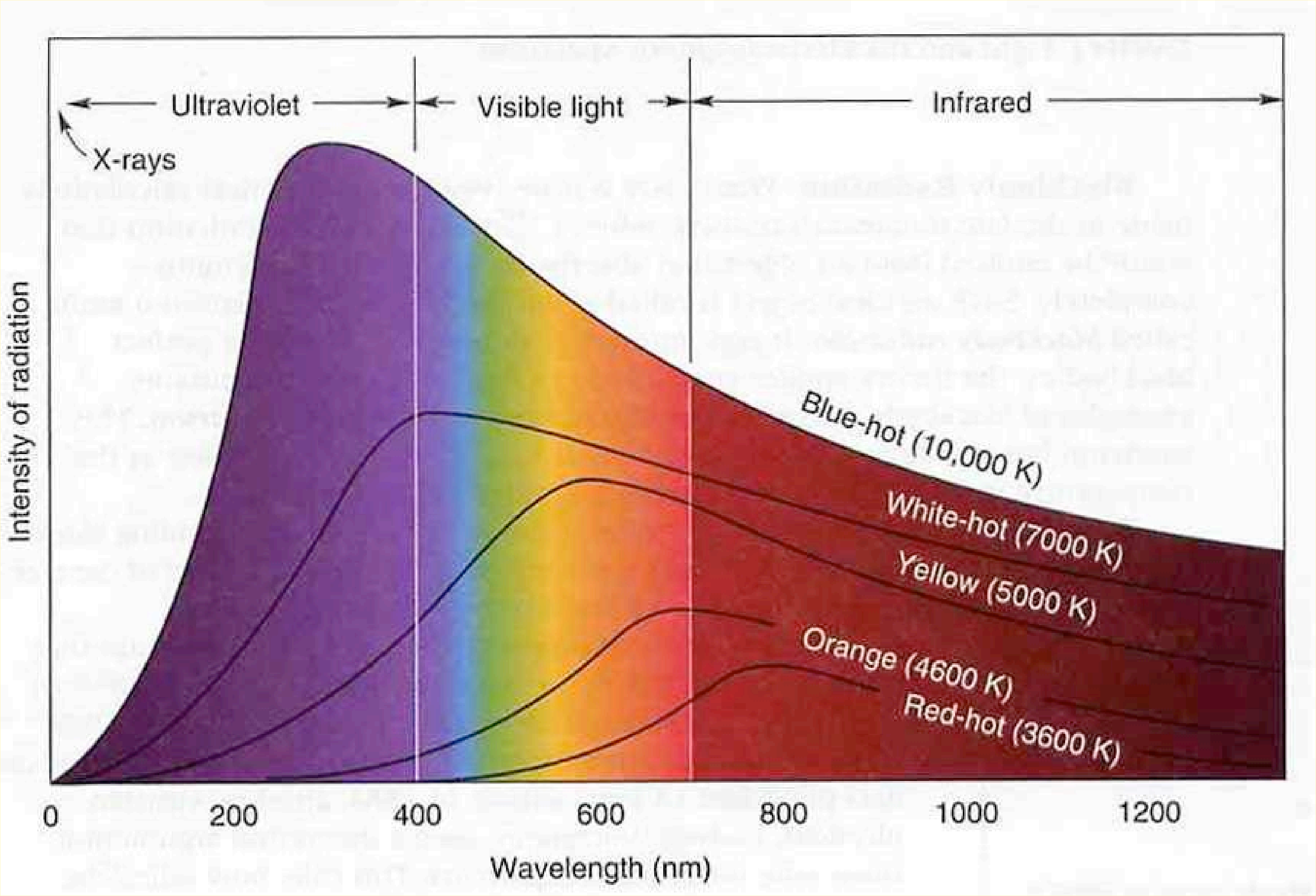


Figure 4-8
The spectrum of light from the taillight of this particular car. The light bulb emits white light, but the plastic cover over the bulb absorbs much of the light, letting pass some wavelengths in the red, orange, and yellow regions of the spectrum.

Blackbody Spectrum--figure below illustrates Wien's law and Stefan-Boltzmann law



Doppler Effect : one of most useful and important techniques used in all of astronomy. We will encounter it again and again.

Wavelength (or frequency) of a wave depends on the relative radial speed of the source and observer.

Radial motion means: motion towards or away; along the line of sight.
The Doppler effect involves *only* this component of motion, the *radial velocity*.

Moving away: wavelengths increase ("redshift")
Moving toward: wavelengths decrease ("blueshift")

Shift in $\lambda \propto$ radial velocity $\Rightarrow$ this is how we get speeds of cosmic objects, stars, galaxies, even expansion of universe.

Actual formula is: λ(apparent)/ λ(true) = 1 + (vel./speed of light)

For most objects in the universe, this relative shift is tiny, so we can't detect it using
the "shift" of the whole spectrum. But we *can* use places in the spectrum whose wavelengths are precisely known $\Rightarrow$ spectral lines (the subject of Chapter 4)