Newton’s laws of motion and gravity

Newton's laws of motion

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*."

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.

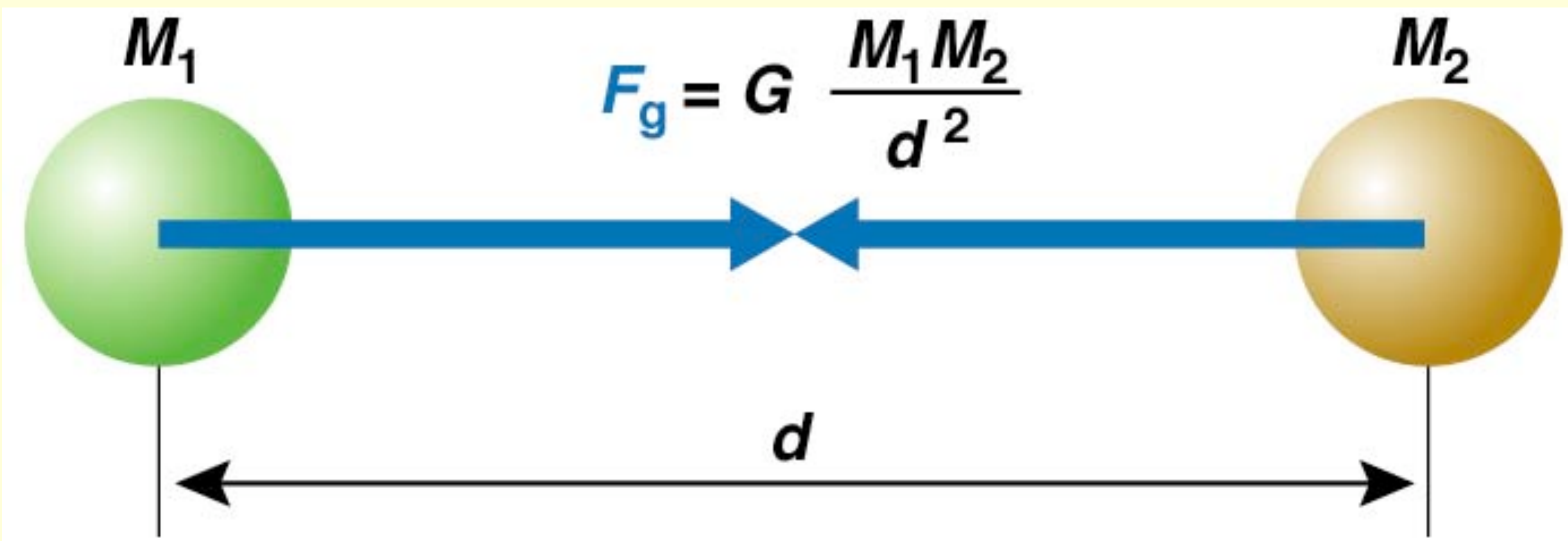
⇒ You can see that if you know the mass of something, and the force that is acting on it, you can calculate its *rate of change of velocity*, **so you can find its velocity, and hence position, as a function of time.**

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 (Newton's law of gravity):

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 (cont'd):

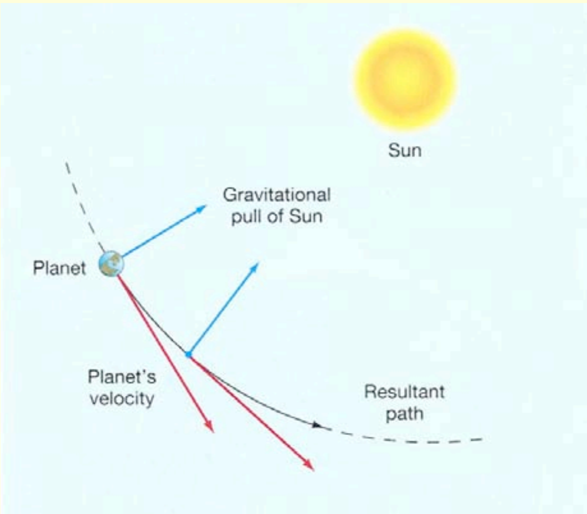
Every object attracts every other object with a force

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

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

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 (see below).

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 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.

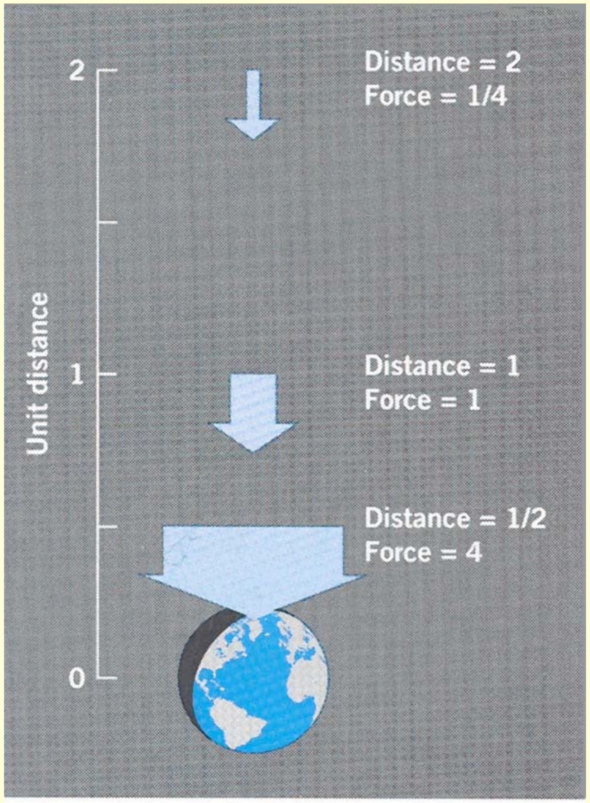


FIGURE 4.17 Moving the same mass at three different relative distances from the earth. For each distance, the thickness of the arrow indicates the relative amount of the gravitational force between the mass and the earth.

But···What *is* gravity?

How is this "force" transmitted *instantaneously*, at a distance?
("Gravitons"--translation: we don't know).

Today, gravity is interpreted as a "field" that is a property of space-time itself, or even stranger interpretations.

Nobody really knows what gravity "is," we just see things falling…

Get used to this: Physics does not know what anything "is" or how it "really works." Another example: What is "light"?

Physics is only concerned with developing models that can explain phenomena and experiments.

So Newton's laws are important only because they allow us to calculate and predict things. But no one knows what "inertia" or "gravity" really are. Some physicists are urging that we remove the word "mass" from the physics vocabulary, because it plays no essential role!

Using Newton's laws, continued···

Applying this procedure (Newton's 2nd law with the law of gravity) you (or at least someone) can derive Kepler's laws, ***if*** you know the form of the gravitational force. For gravity we have Newton's formula

→ $F_{grav} = G\ m_1 m_2/d$

where G is Newton's gravitational constant (you don't have to know it's value), m_1 and m_2 are the two masses, and d is their separation (distance from each other).

From this "it can be shown" that all closed orbits are ellipses, that the orbital motion is faster when the two objects are closer to each other (Kepler's 2nd law), and Kepler's 3rd law, the most important result.
Kepler's third law now 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. We will use this over and over--it is the only way we have to get masses directly.

The most important thing about Newton's laws is that they are *general:* you can calculate the motion of *any* object (or any 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; but it could be frictional force, magnetic force, electrostatic repulsion, ….)

We calculate the evolution of clusters of stars, of millions of galaxies in an expanding universe, of a hot gas in a magnetic field, and almost everything else, although in general this is so difficult that you can only get computer solutions. Example shown on next page.

Examples:

- Earth's orbital period (1 year) and average distance (1 AU) tell us the Sun's mass (think: why don't you need to know the Earth's mass for this purpose?

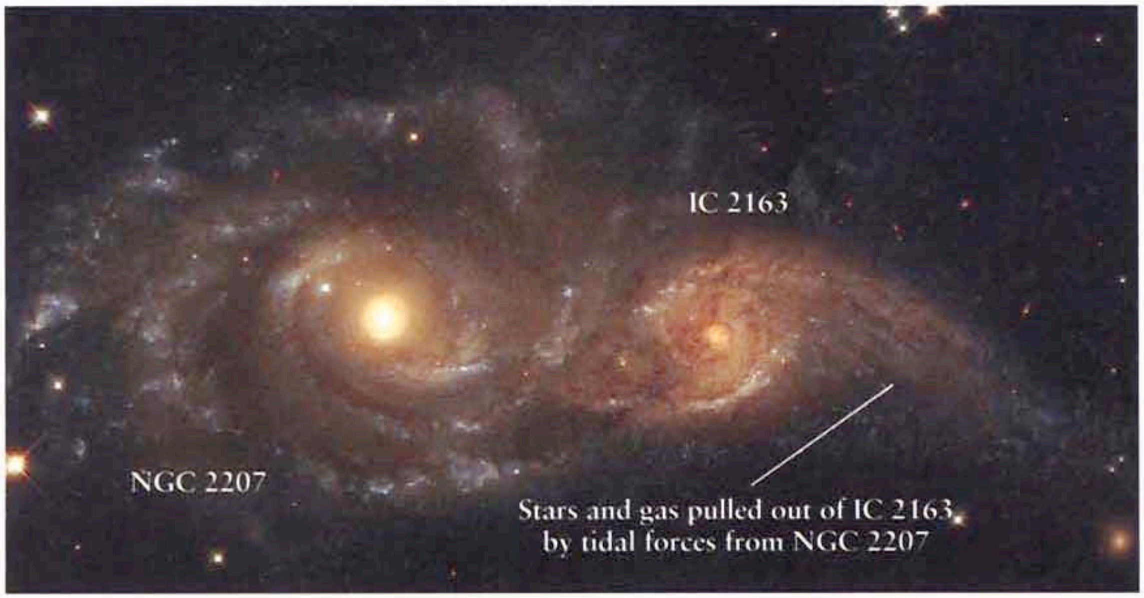
- Orbital period and distance of a satellite from Earth tell us Earth's mass.

- Orbital period and distance of a moon of Jupiter tell us Jupiter's mass.

- This is how "black holes" were discovered to actually exist (later in course), and how the masses of planets orbiting other stars are determined.

- Motion of stars in galaxies reveals the existence of invisible mass, or "dark matter," whose nature remains unknown.

A complex example of the use of Newton's laws: Illustration below shows effect of gravitational forces between two galaxies that are in the early stages of collisional *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 how tidal forces are distorting these galaxies. 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.



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)

End of material on

orbits under gravity,

Kepler's laws,

Newton's laws and

the way Newton's form of Kepler's third law can give us the *masses* of astronomical objects. In fact it is just about the *only* way.

How else can you learn about astronomical objects? All you get from them is their *light*, so there are two chapters just on how we can analyze light.

Light: Properties

Properties of Light (ch. 3 in text)

This is an extremely important topic, because the only things we can learn about objects and phenomena outside our solar system are learned 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. It won't be on the exam.)

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

Wavelength—Always denoted by Greek letter "λ".

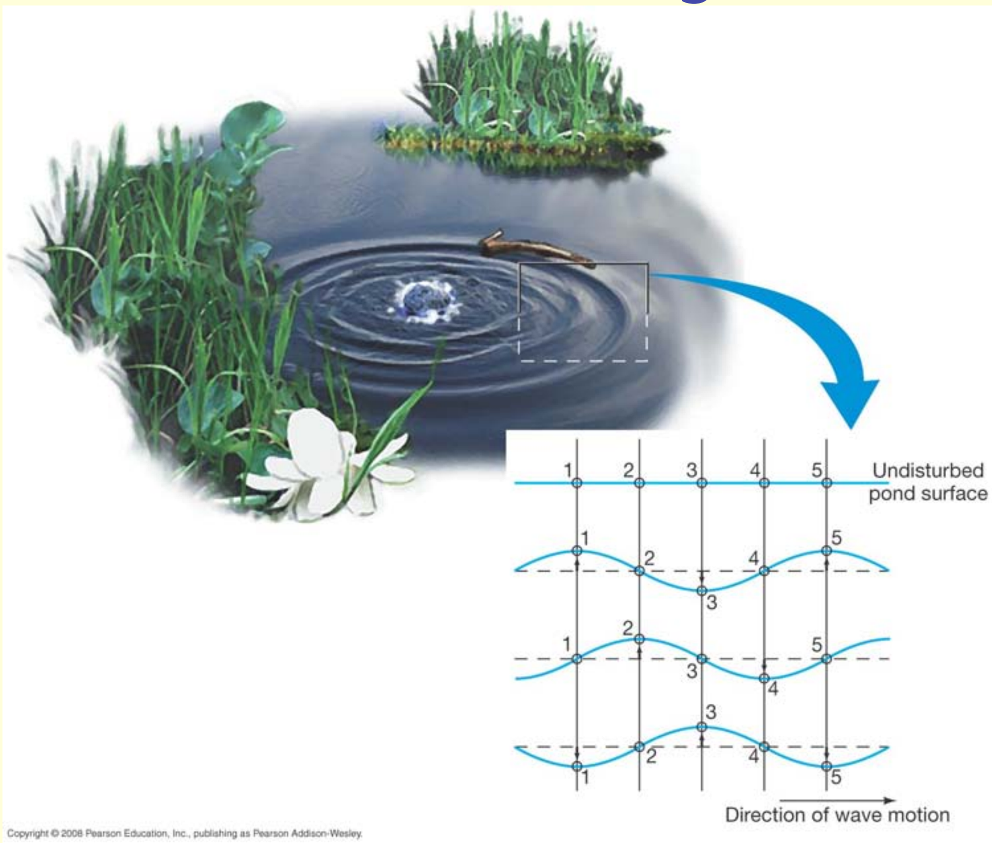
Frequency—how many waves pass per second, denoted "f" or "ν"

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. See pp. 65-66 of textbook, and illustration on next slide.

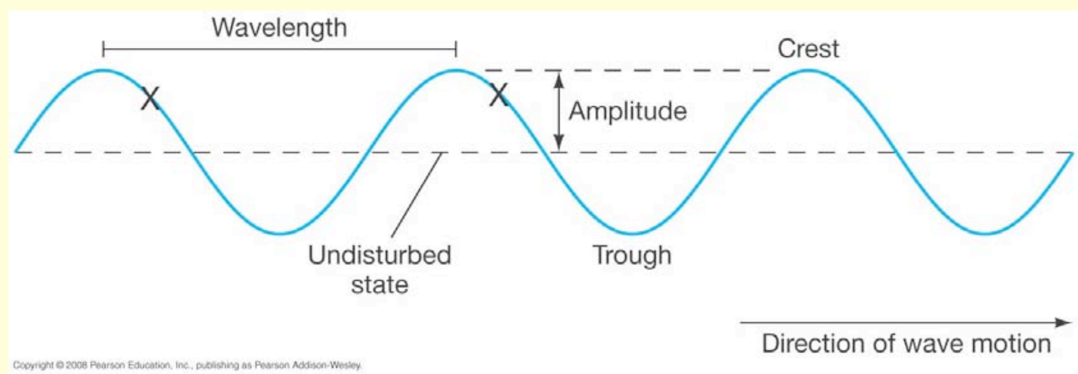
Illustrating wavelength, frequency



Imagine pebble dropped in pond: surface waves will appear to travel outward.

Distance between peaks or troughs = *wavelength*

How many peaks or troughs pass by you per second? = *frequency*



➞ 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. See illustrations in sec. 3.3. 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*.

The restriction of human wavelength sensitivity

Human vision is only sensitive to a very tiny fraction of all this radiation, the "visible" or "optical" part of the spectrum—astronomy in the last 50 years has been mostly concerned with getting *out* of this region. That is probably the single most important technical revolution in astronomy-- for most of this radiation you have to be above the Earth's atmosphere.

Atmospheric absorption and "windows"

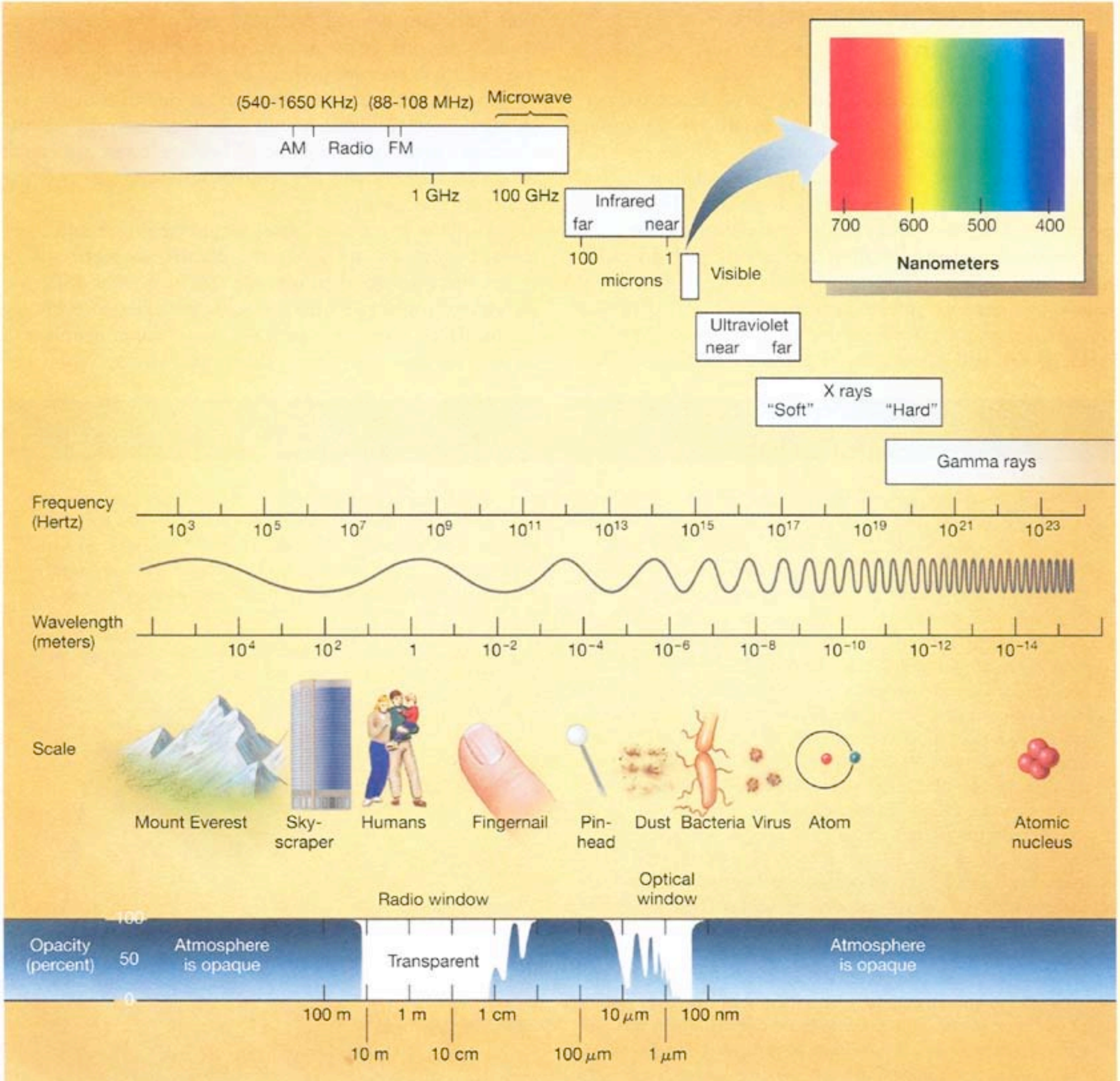
Earth's atmosphere is very *opaque* (light can't get through) except in the visible (also called "optical") and radio parts of the spectrum (the so-called optical and radio "windows"). That's why much of recent astronomy is done from satellites. See p. 70 of textbook on "atmospheric opacity" and get used to the word "opacity."

Illustrations of the various wavelength regions

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 next illustration is just an alternative presentation of the same information.

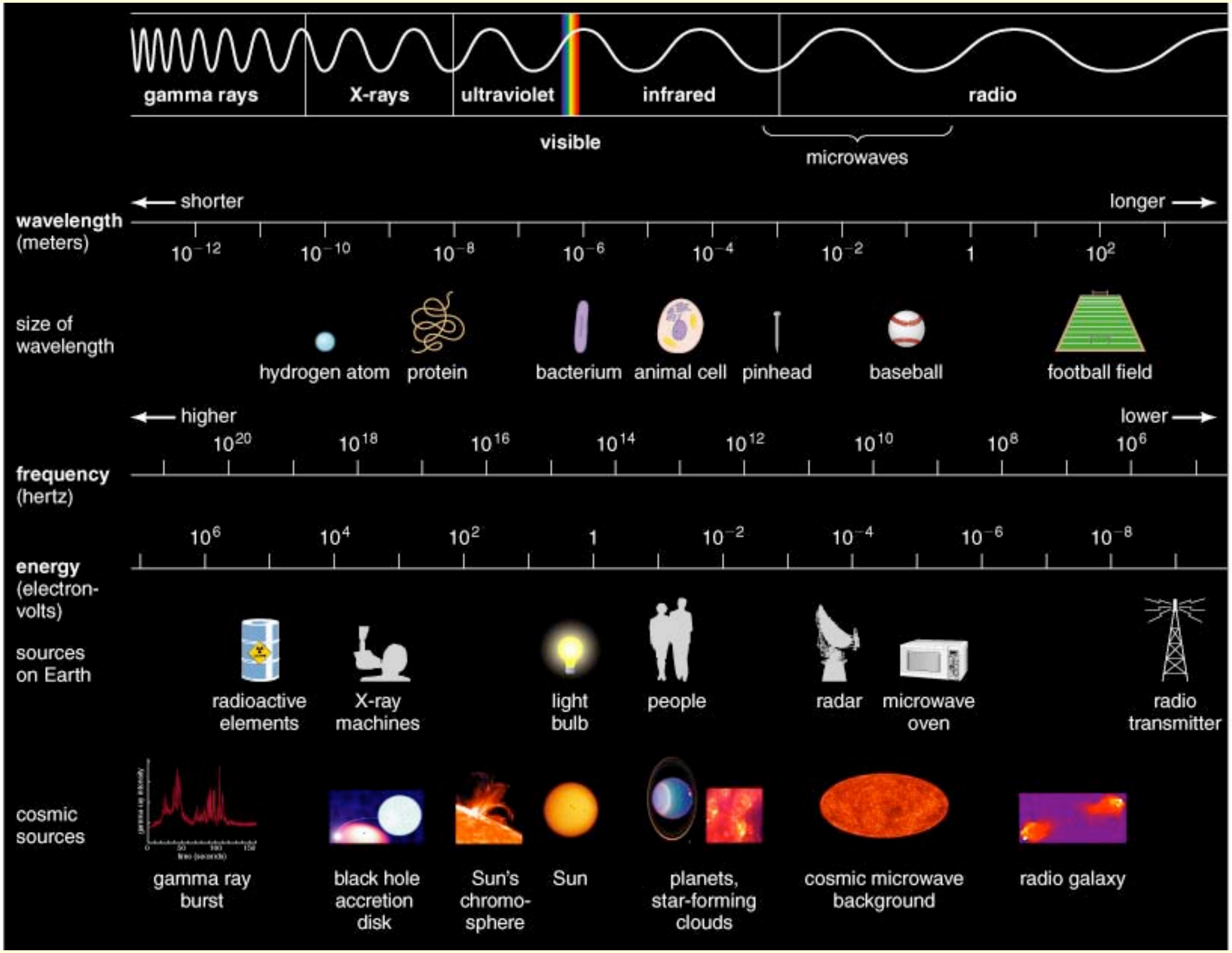
The third illustration is worth studying: Earth’s atmospheric windows.

NOTE: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



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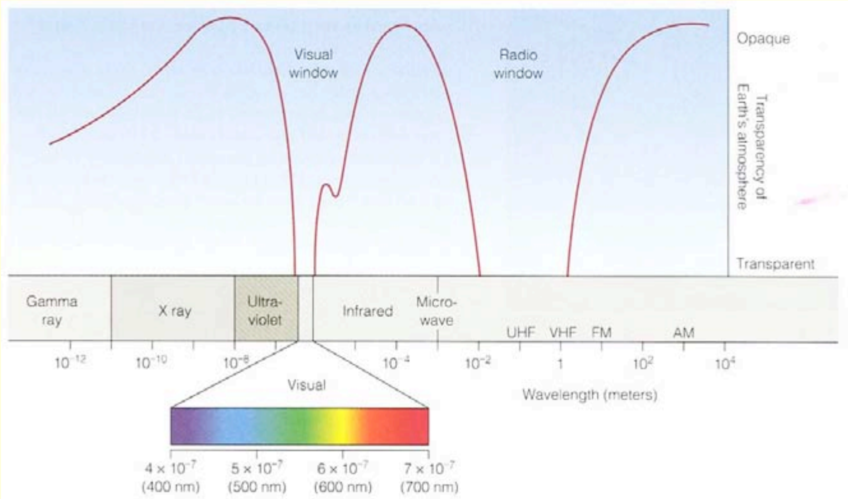
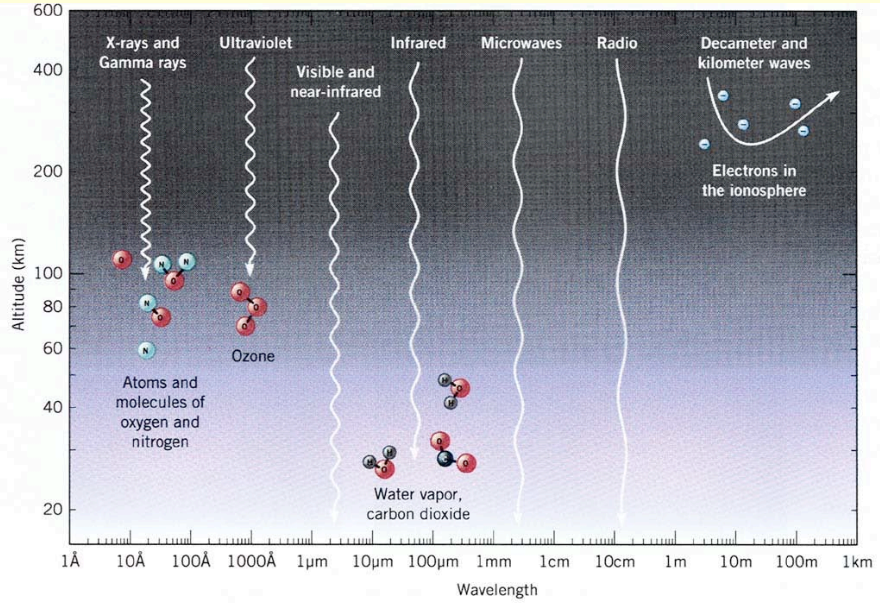




Spectra: what they are, why they are useful

(note-this is the beginning of a very long list of uses)

Spectra of lemons and car tail lights

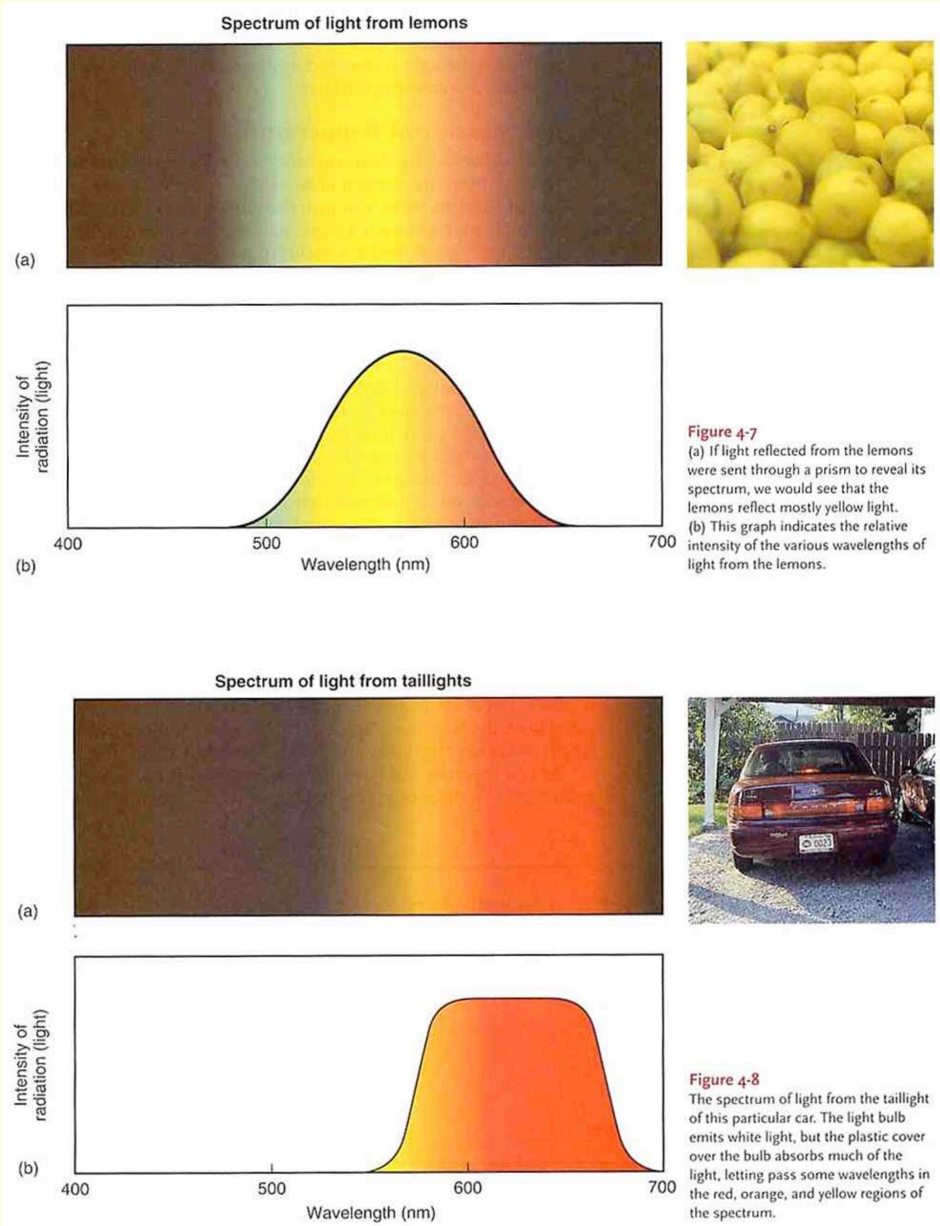


Figure 4-7
(a) If light reflected from the lemons were sent through a prism to reveal its spectrum, we would see that the lemons reflect mostly yellow light. (b) This graph indicates the relative intensity of the various wavelengths of light from the lemons.

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.

In each case the top picture shows how the spectrum appear in a *spectrometer*; *the bottom picture is a graph of the spectrum as intensity versus wavelength, which is how the idea should be understood.*

The first representation has vertical "bands" only because of the design of the instrument. You will see lots of these in your reading: Always try to think of them in terms of intensity vs. wavelength (or frequency) instead.

You will need to keep this in mind:
A "spectrum" is a graph showing the relative amount of light emitted as a function of wavelength.

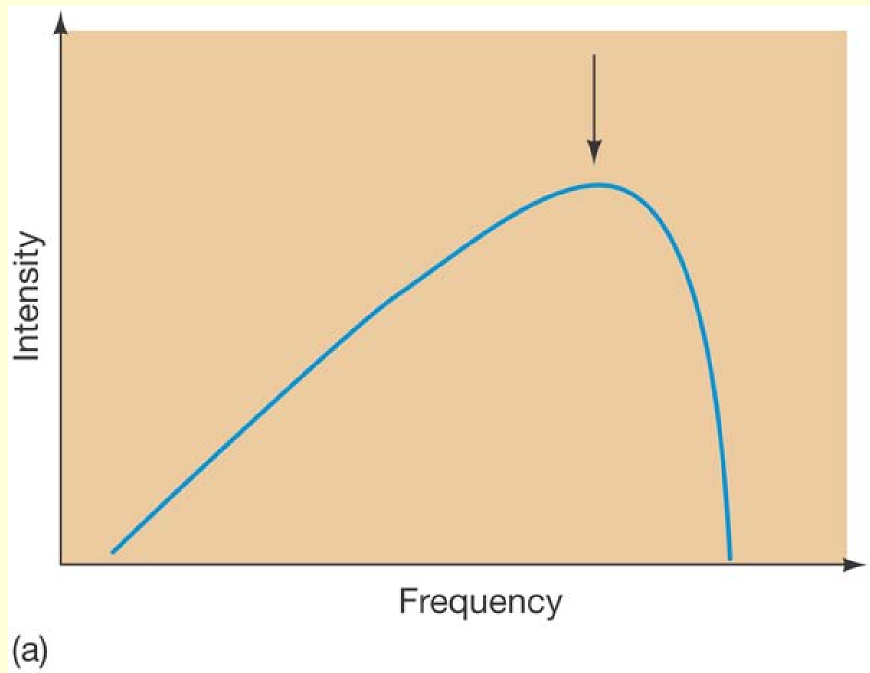
Black-Body Spectrum

A "black-body" (BB) is only a simplified mathematical model, but works surprisingly well for the continuous (smooth) spectra of objects. See Fig. 3.10 and graphs after this page.
The model predicts an <u>equation</u> for the *continuous* **spectrum** (intensity vs. wavelength or frequency--be sure you understand this word!) of such an ideal object, for any temperature.

"Continuous" means it is a smooth curve (compared to the "spectral lines" that real objects exhibit, and which we will study later, in Ch. 4).

The graph to the right is an example of a blackbody spectrum. It is smooth (continuous), with a peak at some definite frequency (wavelength). Understand it as showing the number of photons that are emitted by this object at each interval of frequency (wavelength)

This is the wavelength of peak emission that is called λ_{max}. Wien's law says that λ_{max} increases with decreasing temperature. Which direction is this on the graph below?



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/(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 an object's surface temperature from the spectrum.* (See fig.3.11 in text)

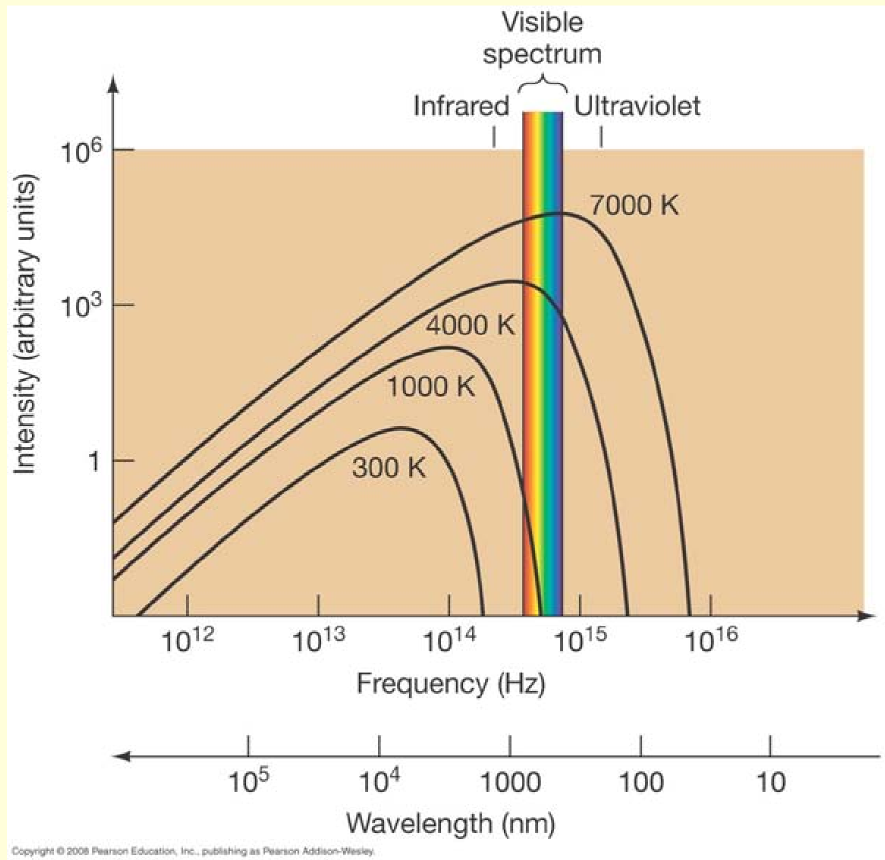
2. Stefan's law: TOTAL energy E radiated at *all* wavelengths (*per unit surface area*, meaning per square inch, or per square meter, or per square anything) is related to the temperature by:

$E \propto (\text{temperature})^4$ → **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. 3.12 (BB curves for 4 cosmic objects) on next page.*

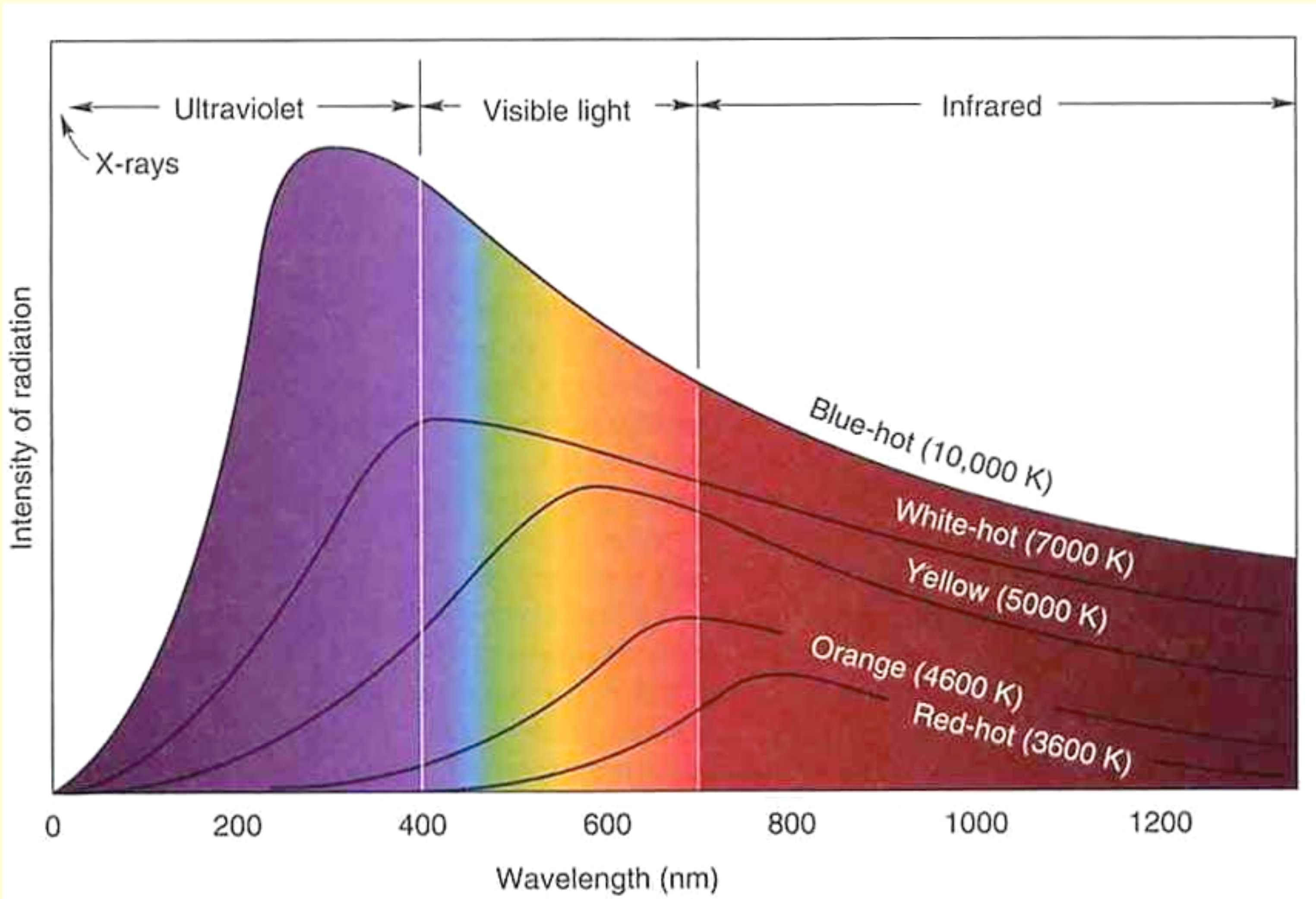
This graph shows blackbodies with four temperatures T. As T increases, λ_{max} decreases (Wien), and the total energy under each curve *increases* (Stefan-Boltzmann)

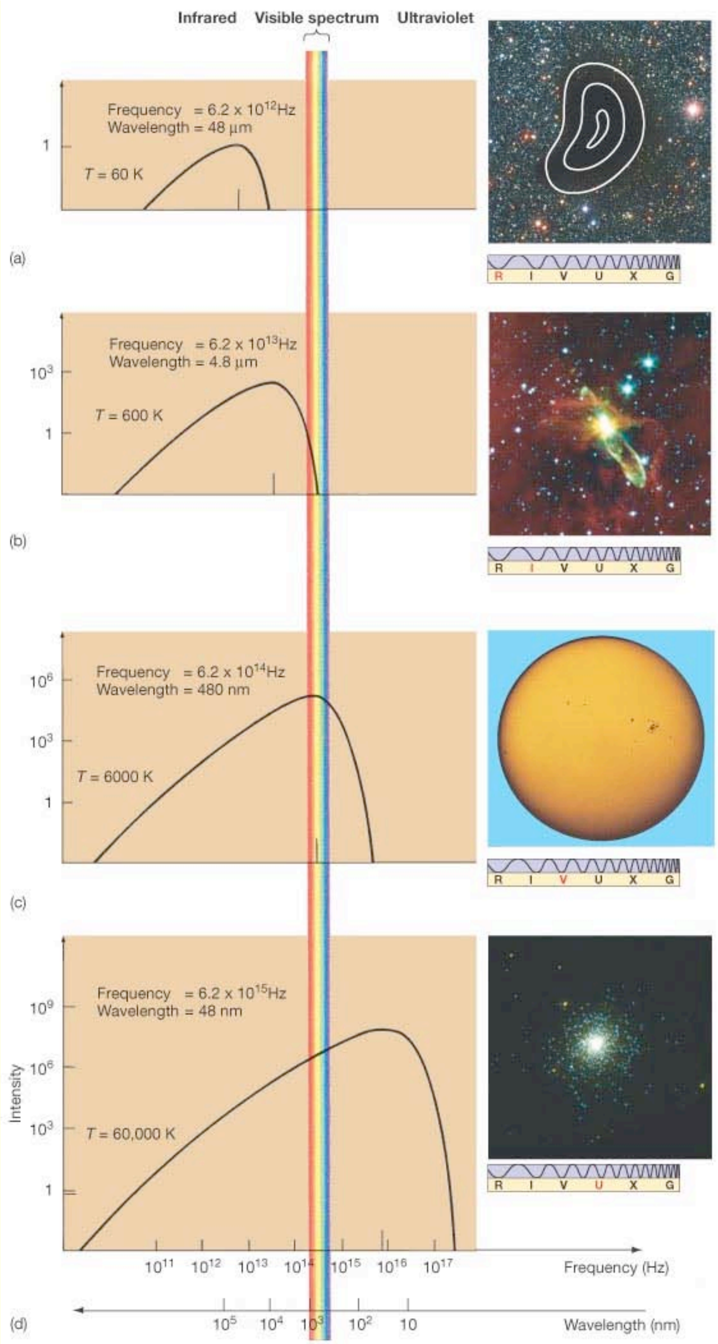


→ Which spectrum above could be the spectrum of an object at room temperature?

→ Which could be a star?

Blackbody Spectrum: figure below illustrates Wien's law and Stefan-Boltzmann law (again)





Blackbody spectra at the temperatures of four astronomical objects

Carefully compare the graphs with the temperatures given for each object.

Notice that the coolest of these is only 60 degrees above absolute zero, while the hottest is ten times hotter than the Sun's surface.

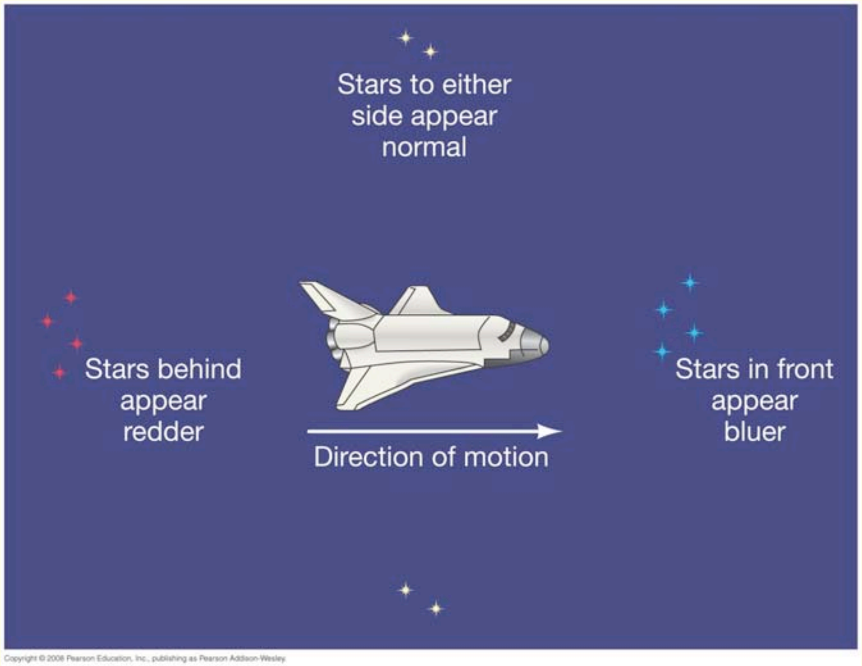
We may SKIP THIS until exam 2

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")



How the Doppler effect allows you to calculate how fast things are moving, and why you can't use it for a continuous spectrum

Shift in wavelength gives radial velocity. This is how we get speeds of cosmic objects, stars, galaxies, even expansion of universe.

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

where the $\pm$ sign means it is + if it is moving away from us (redshift, longer wavelength), - if it is moving toward us (blueshift, shorter wavelength)

Look at this formula: If velocity of object away or toward us is much less than the speed of light (true for almost all objects in the universe), the apparent wavelength will be only slightly different from the "laboratory" or "rest" wavelength.

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

End of material for exam 1