Some Introductory Concepts

Scientific notation for very large and small numbers (read Appendix 1 in text). Example: 3×10^6 = 3 million, 4×10^{-3} = 0.004. You will continuously encounter this notation, so become comfortable with it now (even though I will not ask you to manipulate such numbers on exams). Just get used to it—try writing down a few yourself—e.g. two million, 3 one-thousandths, …

Units of length, size, mass, … Defined just for convenience. Example: for distance or size, could use "microns" for light or dust particles, "centimeters" or "inches" for everyday objects, "light years" or "parsecs" for stars, "megaparsecs" for galaxies.

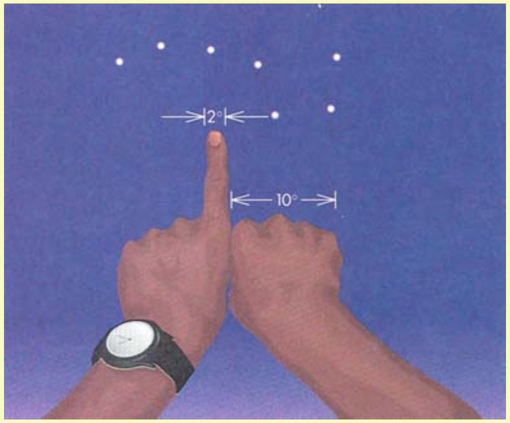
Appendix 2 in the textbook goes over some of this; just skim it now and use it for future reference if you become confused about units. But we will only be using a few units in this class, so it shouldn't cause any problem.

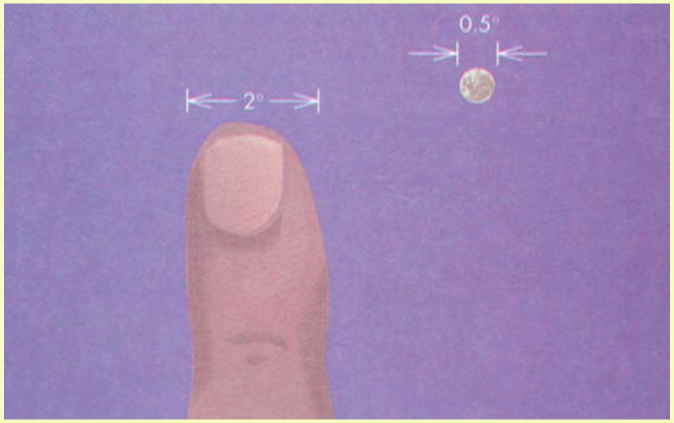
Another example: it is convenient to state the masses of astronomical objects in units of the Sun's mass, e.g. "200 solar masses" or "200 Msun" instead of writing "4×10^{35} grams." The mass of many galaxies (including our own) is in the range 10^9 to 10^{12} solar masses, so you can see there is no escaping scientific notation, even if we use a convenient unit. The range of properties of astronomical objects is just too large.

Angular measure (box, p. 11) –degree, arcminute, arcsecond (especially important). Most astronomy today commonly break the "arcsecond barrier" imposed by our own Earth's atmosphere. (This effect, called "scintillation," is due to the turbulence in the Earth's atmosphere, which makes stars "twinkle.")

Angular measure using "*arcsecond*" terminology will occur in many places throughout the course (first in connection with "parallax").

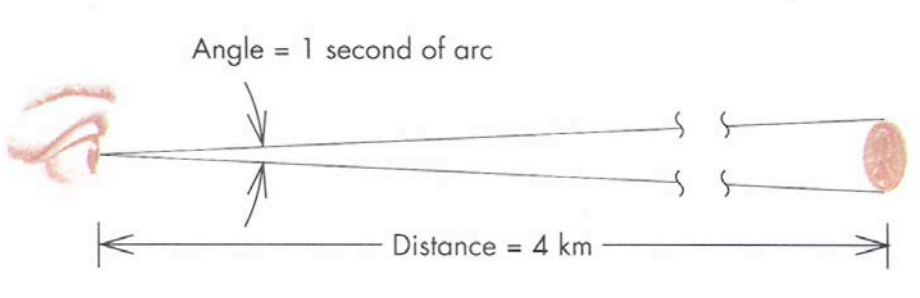
The term for the smallest angular size at which you can distinguish objects is called "angular resolution," a phrase you will encounter frequently. Can remember what resolution means by keeping in mind that poor resolution is like being very nearsighted—everything looks blurry.





One Second of Arc

A penny at a distance of 4 km (2.5 miles) has an angular diameter of 1 second of arc.



Constellations: These are just apparent groupings of stars in the sky; they are (usually) not physically associated, and could be at very different distances (see Orion example).

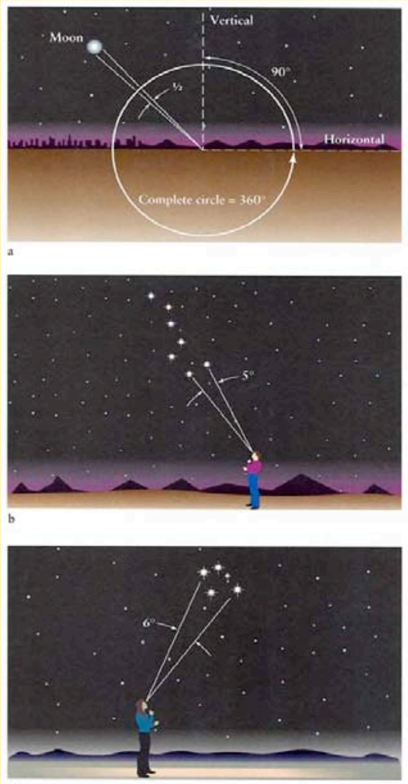
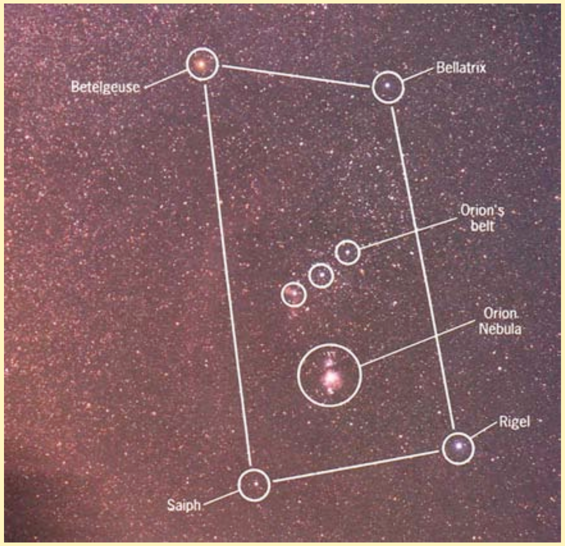
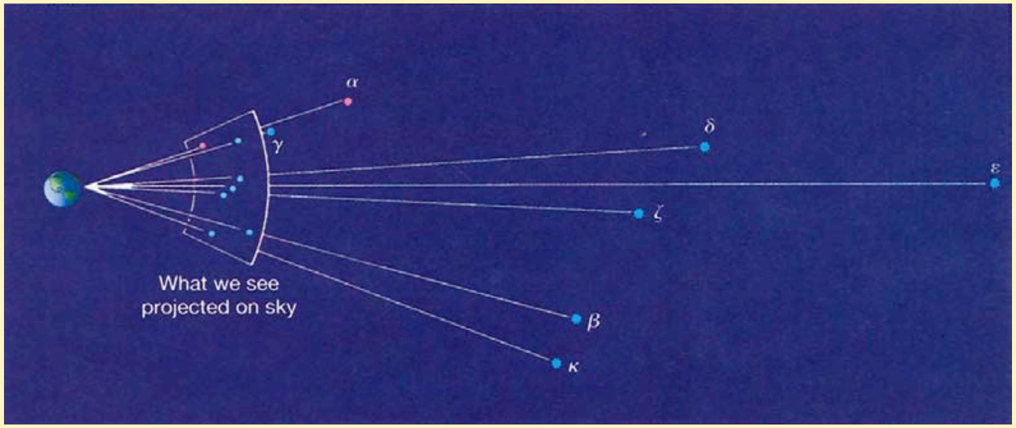


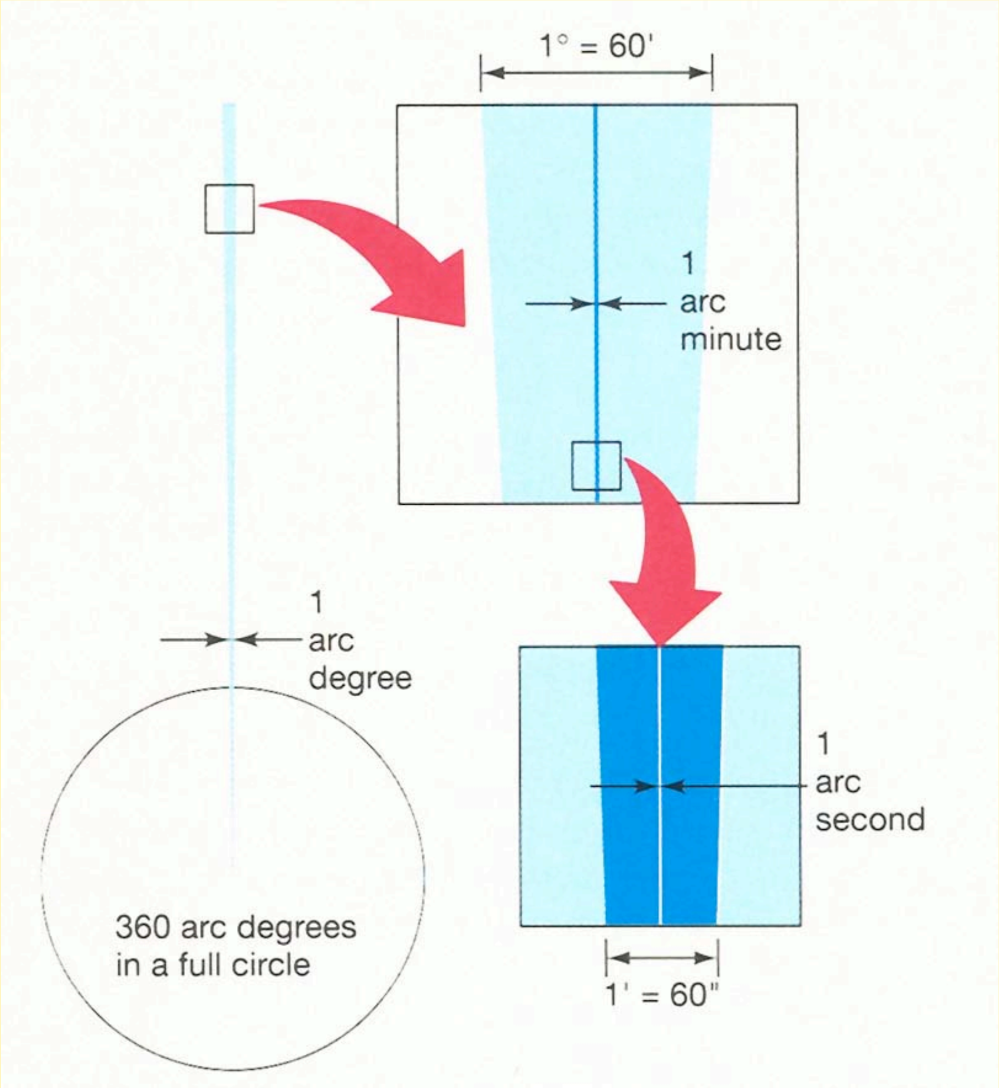
Figure 1-9

Angles and Angular Measure **(a)** Angles are measured in degrees (°). There are 360° in a complete circle and 90° in a right angle. For example, the angle between the vertical direction (directly above you) and the horizontal direction (toward the horizon) is 90°. The angular diameter of the full moon in the sky is about ½°. **(b)** The Big Dipper is an easily recognized grouping of seven bright stars, visible from anywhere in the northern hemisphere. The angular distance between the two pointer stars at the front of the Big Dipper is about 5°, roughly ten times the angular diameter of the Moon. **(c)** The four bright stars that make up the Southern Cross can be seen from anywhere in the southern hemisphere. The angular distance between the stars at the top and bottom of the cross is about 6°.

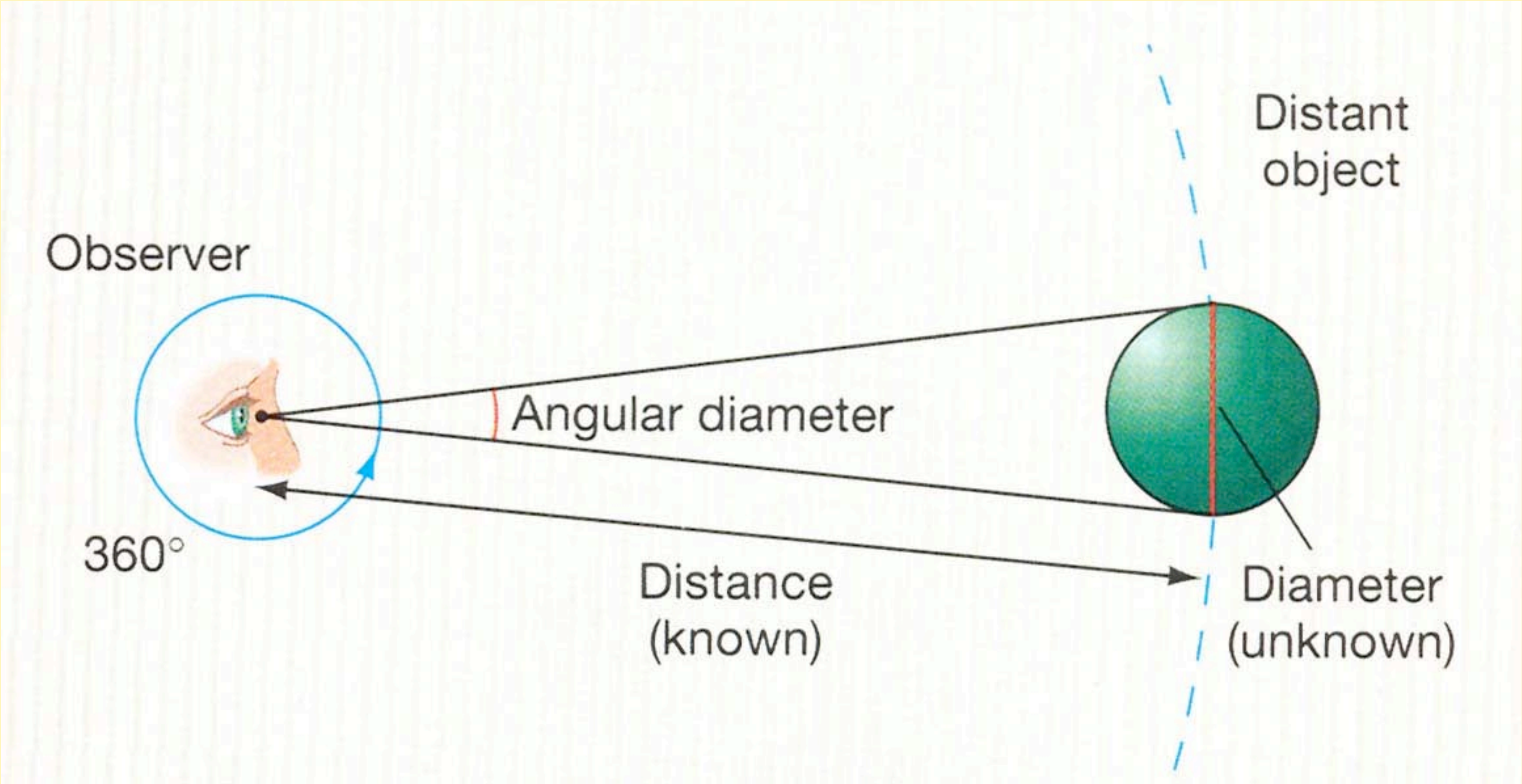




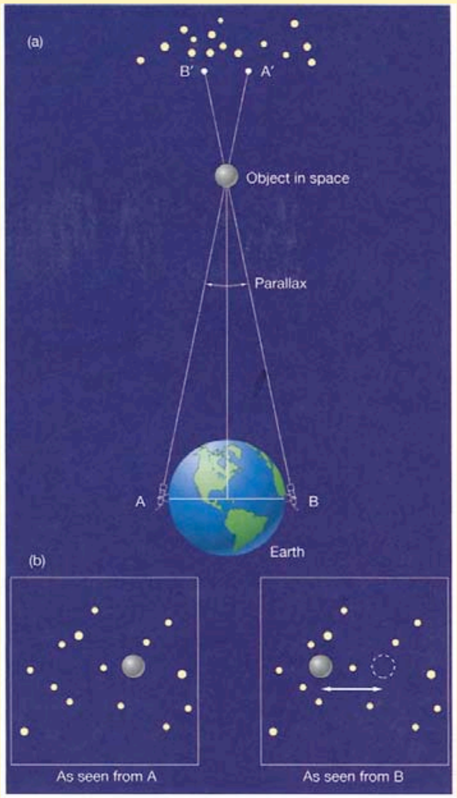
Angular measure--illustration from your textbook.



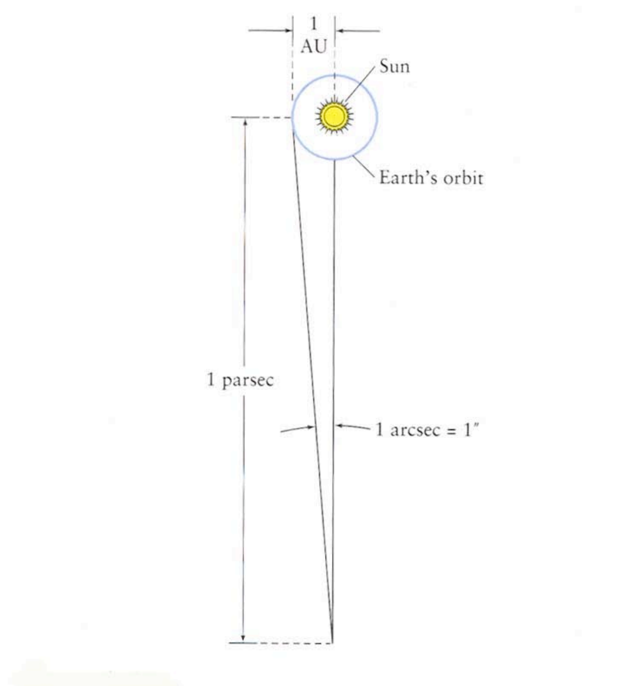
Angular diameter of an object--notice how you could get the distance of the object if you knew its size, or its size if you knew its distance. (The formula is that diameter = distance x angular diameter (in "radians".) But if you can't "resolve" the object, then you can't use this method at all (e.g. for stars). Make sure you understand what this means!



Distances from **Parallax** Angle (sec. 1.7 in text)



▲ **FIGURE 1.31** **Parallax** (a) This imaginary triangle extends from Earth to a nearby object in space (such as a planet). The group of stars at the top represents a background field of very distant stars. (b) Hypothetical photographs of the same star field showing the nearby object's apparent displacement, or shift, relative to the distant, undisplaced stars.



A Parsec The parsec, a unit of length commonly used by astronomers, is equal to 3.26 light-years. The parsec is defined as the distance at which 1 AU perpendicular to the observer's line of sight subtends an angle of 1 arcsec.

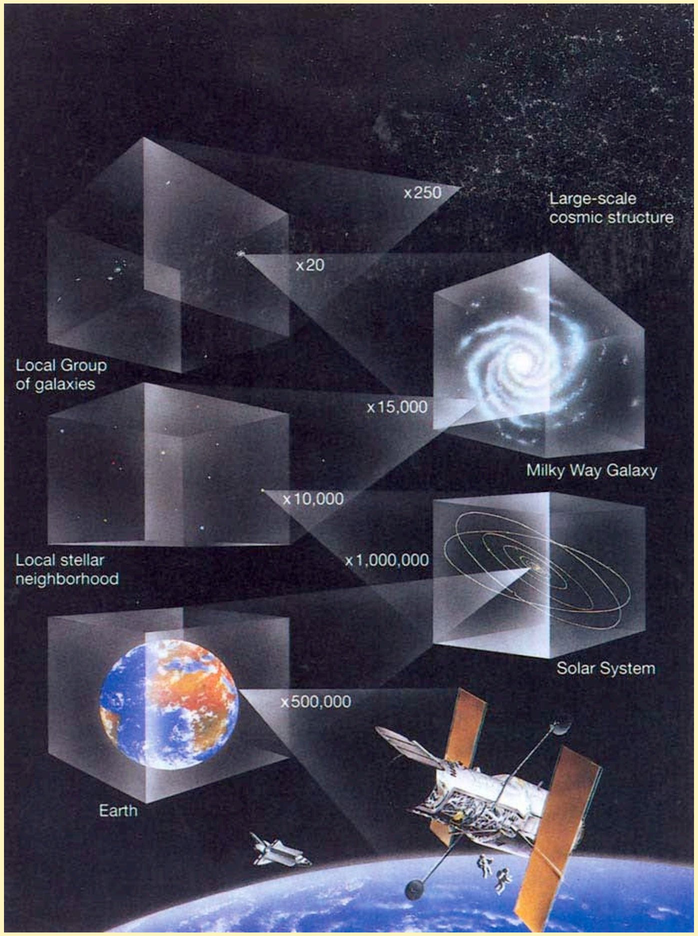
Left: Parallax using diameter of Earth. Understand why baseline is too small for stellar distances.

Right: Parallax using 1AU→ defines the unit of distance called a "parsec" (for distance of object whose <u>par</u>allax is one <u>sec</u>ond of arc (one arcsec).

Distances and sizes in the universe

The measurement of distances to stars by parallax is the first step in a long line of methods to learn about the scale of the universe at larger and larger distances. Can only use parallax for nearest ~ few 100 pc (because stars more distant than that have parallaxes so small that they can't be measured (yet), even from space.

What we end up with is an amazing range of sizes and distances of various objects in the universe, as shown in the illustration to the right (from your text; good idea to stare at it a while). But parallax is only the first step.

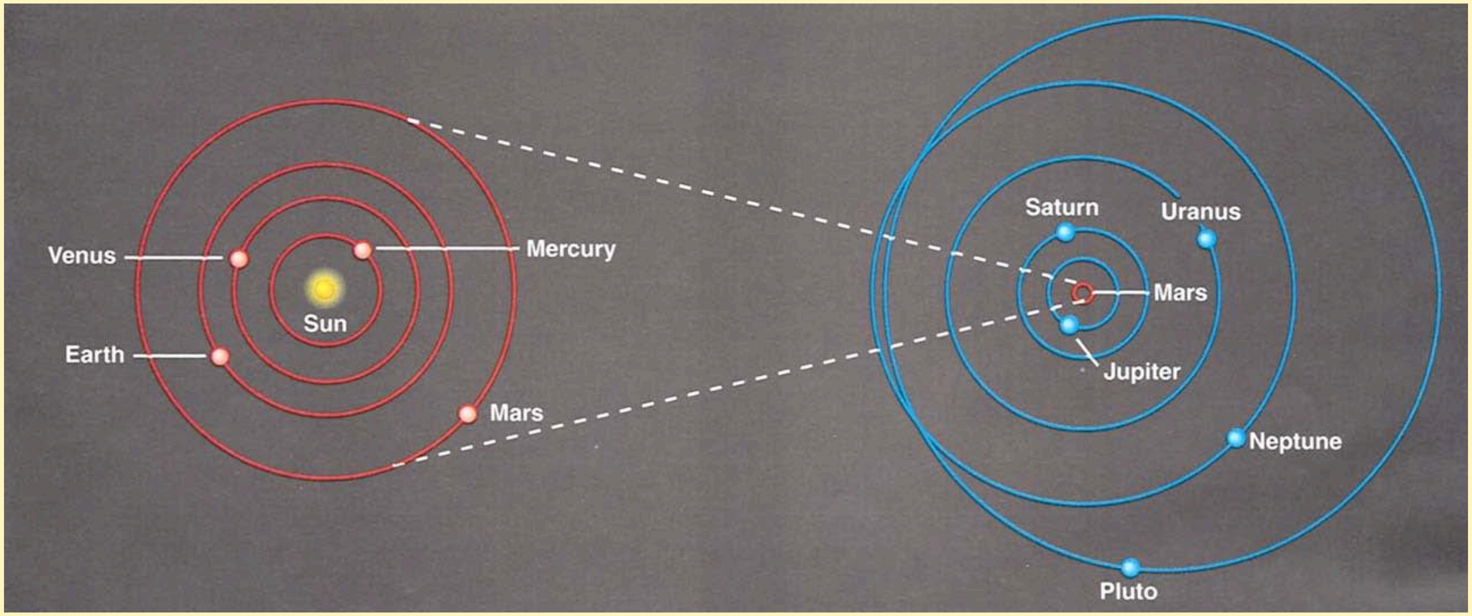


Distances: We'll return to parallax in more detail later in the course: for now you should just get the basic idea, and how it relates to the unit of distance called "*parsec.*"

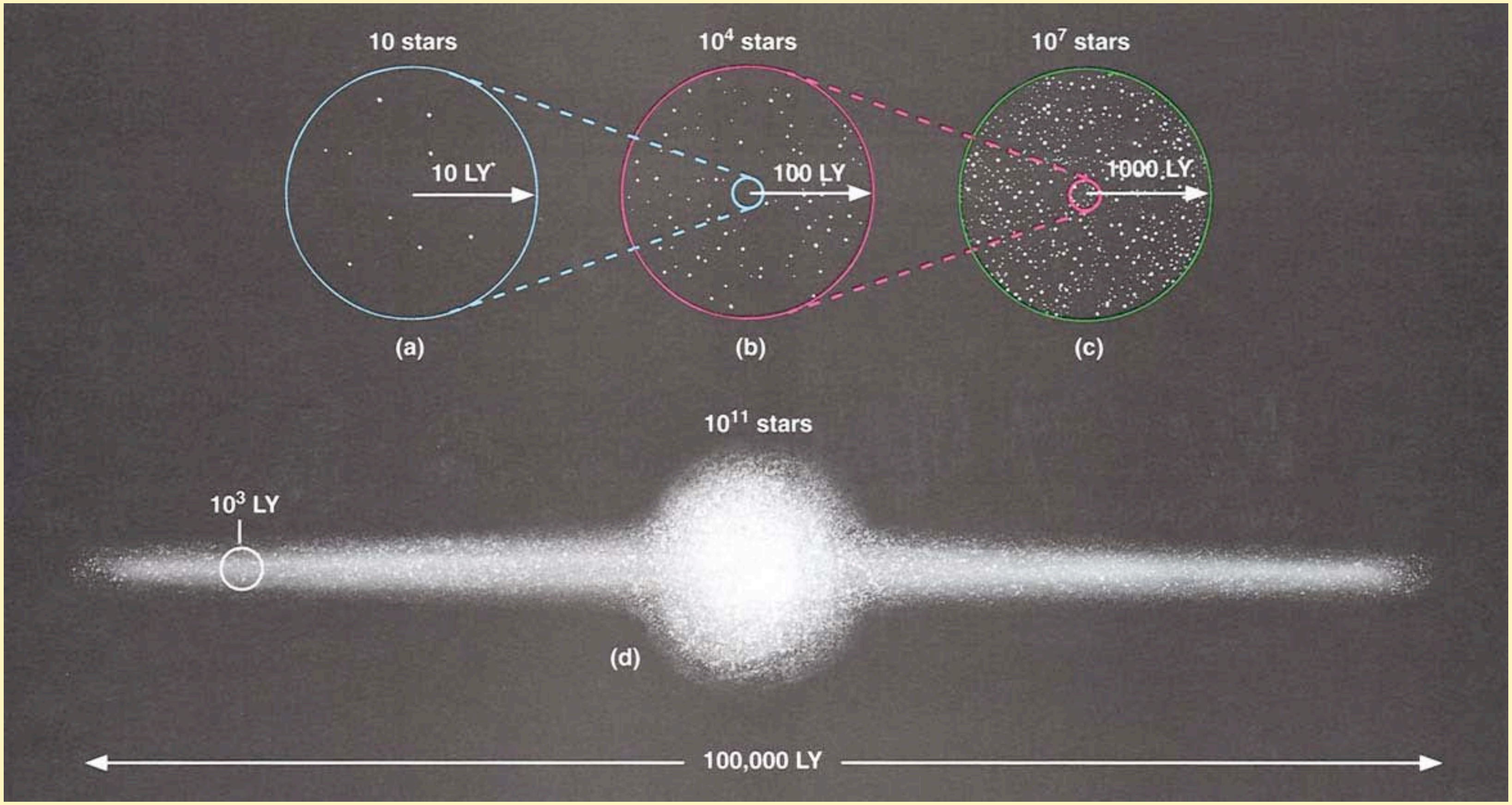
Nearest stars are about 1 pc (a few light years) away. This is also the average distance between neighboring stars in most galaxies. It is a number that you should remember.

Size of our Galaxy and many others is about 10,000 pc, and the distances between galaxies range from millions (Mpc) to billions of pc (1000 Mpc—make sure you are comfortable with what this means--see preceding figure again).

For distances in the solar system, see sec. 2.6. Average distance from Earth to Sun defined as "*astronomical unit*" (1AU) (~ 10^{-3} pc), size of our solar system ~ 100 AU.



As we move out from the solar system to see the nearest stars, the scale of distances expands enormously--100AU is *tiny* compared to the average distances between stars, and nearly infinitesimal compared to the sizes of galaxies or larger structures in the universe.



Geocentric vs. heliocentric model (sec. 2.2-2.4)

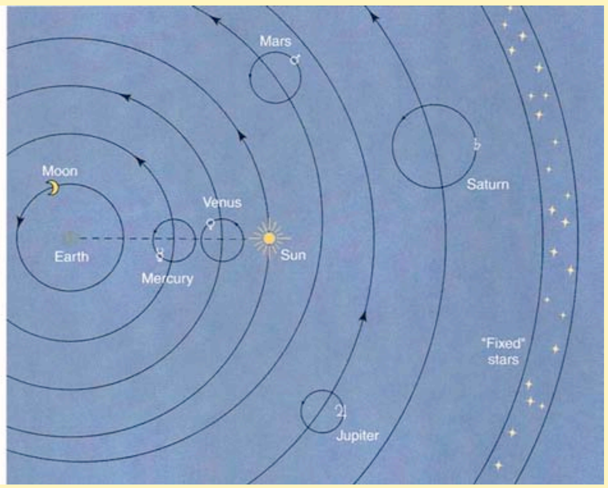
Ptolemy (~140 AD) … Copernicus (~1500 AD), Galileo (~1600), Tycho Brahe, Kepler (2.5), Newton (2.6).

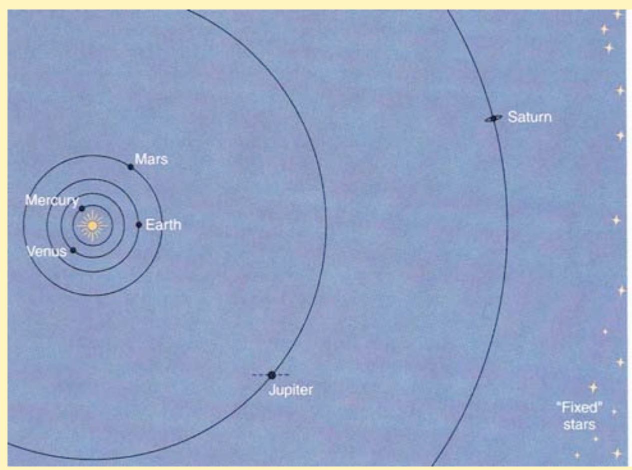
Important to recognize the change in world view brought about by:

Geocentric model (Ptolemy, epicycles, planets asnd Sun orbit Earth)

→ *Heliocentric model* (Copernicus, planets orbit Sun)

The solar system as conceived by Ptolemaic astronomers between about 100 and 1500. Ptolemaic astronomers made rough predictions of planetary motions, using a theory in which the Sun and other planets moved in circular orbits around a stationary, central Earth. Superimposed on the larger orbits were smaller circular motions called epicycles, introduced to try to make the theory more accurate.





The solar system as it might have been conceived around 1700, at the end of the Copernican revolution. The diagram shows the orbits of the 10 known planets to true scale. The view is correct except that the outermost planets (Uranus, Neptune, and Pluto) and the asteroids had not yet been discovered. Compare with Figure 3–2 to see the change from the Ptolemaic view.

Kepler's Laws

Empirical, based on observations; NOT a theory (in the sense of Newton's laws). So they are "laws" in the sense of formulas that express some regularity or correlation, but don't *explain* the observed phenomena in terms of something more basic (e.g. laws of motion, gravity--that waited for Newton)

1.Orbits of planets are *ellipses* (not circles), with Sun at one focus.

Must get used to terms *period* (time for one orbit), *semimajor axis* ("size" of orbit), eccentricity (how "elongated" the orbit is), *perihelion* (position of smallest distance to Sun), *aphelion* (postion of greatest distance to Sun)

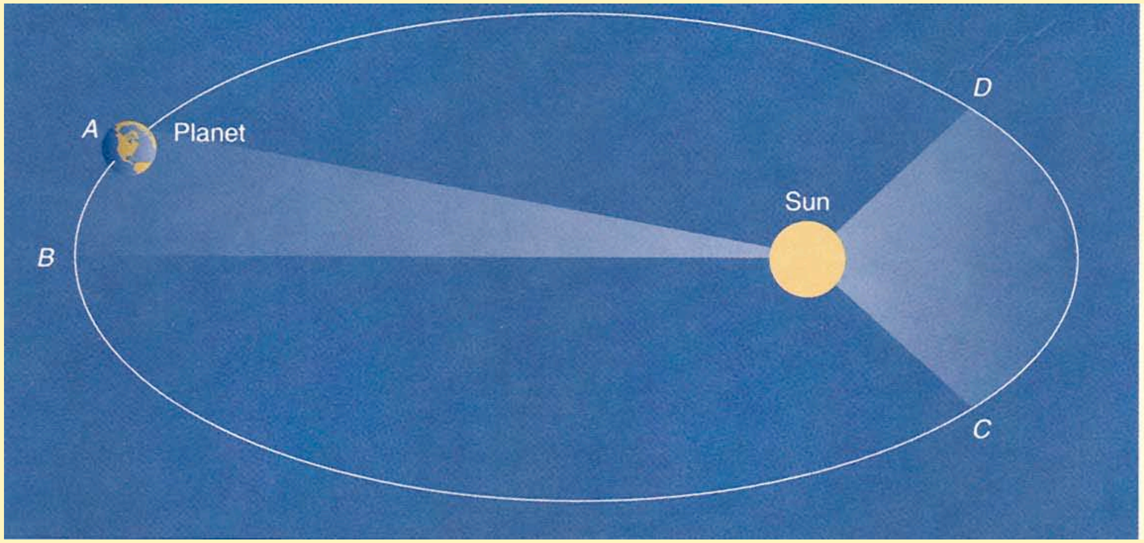
Examples: comets, (most) planets

Escaping from the assumption of perfect circles for orbits was a major leap, that even Copernicus was unwilling to take.

Kepler's 2nd law:

2. Equal areas swept out in equal times; i.e. <u>planet moves faster when closer to the sun.</u>

Good example: comets (very eccentric orbits, explained in class).



Kepler's second law of planetary motion. The orbit sweeps out an ellipse where an imaginary line connecting the planet to the Sun sweeps out equal areas in equal time intervals. The time taken to move from *A* to *B* equals the time taken to move from *C* to *D*. In other words, planets travel faster when they are close to the Sun and more slowly when they are far from the Sun. The true planet orbits are much closer to circles, and the speed only changes by a small percentage along the orbit.

Kepler's 3rd law: Square of the period "P" is proportional to the cube of the semimajor axis "a"

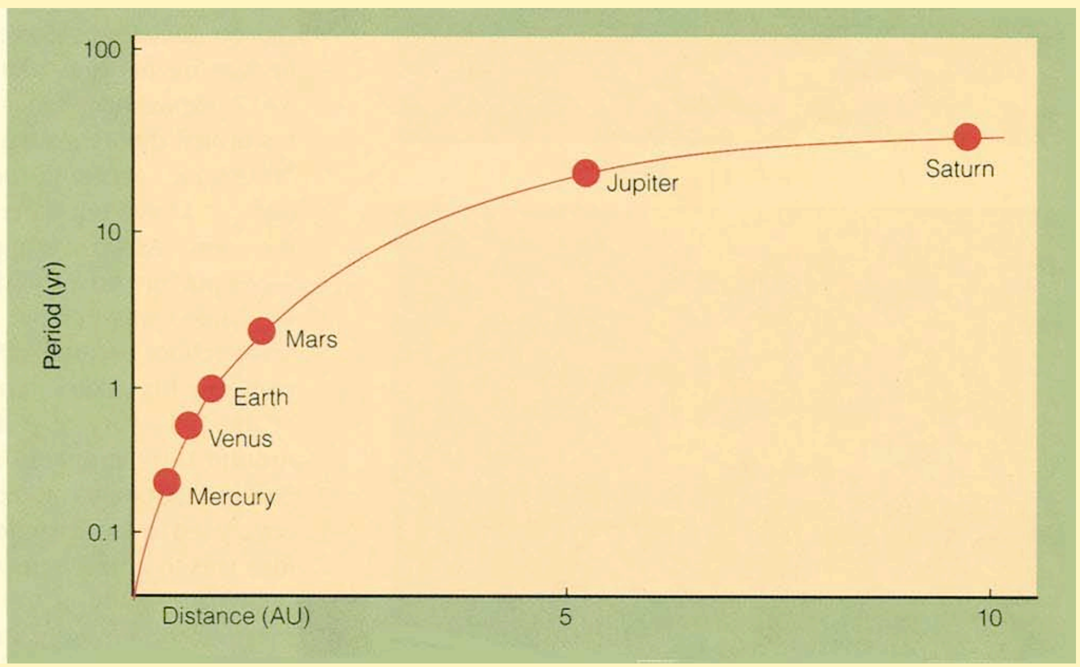
$$P^2 = a^3$$

when P is expressed in Earth years and "a" is in units of A.U. (astronomical unit; average distance from Earth to Sun).

(Absolute size of A.U. unit determined from radar observations of Venus and Mercury, and other methods--see textbook.)

Kepler's 3rd law, as modified by Newton (see below), will be a cornerstone of much of this course, because it allows us to estimate **masses** of astronomical objects (e.g. masses of stars, galaxies, the existence of black holes and the mysterious "dark matter").

Example: The planet Saturn has a period of about 30 years; how far is it from the Sun?



Kepler's third law of planetary motion. The period of a planet's orbit increases with increasing distance from the Sun. Planets discovered after the invention of the telescope obey this law, too. Notice that according to Kepler's law, planets can have properties that place them *anywhere* on this curve. The planets of the solar system have a particular pattern in their spacing from the Sun.

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*.

This tendency 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.

3. To every action, there is an equal and opposite reaction, i.e. forces are mutual.

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

$$F \text{ (gravity)} = (\text{mass } 1) \times (\text{mass } 2) / R^2 \text{ (distance squared)}$$

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.

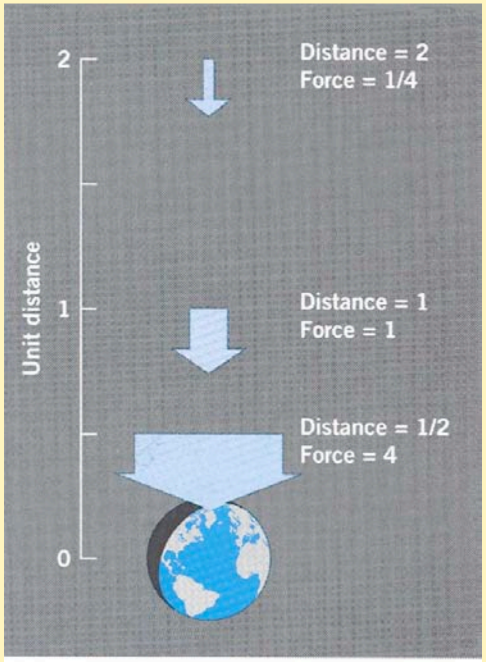
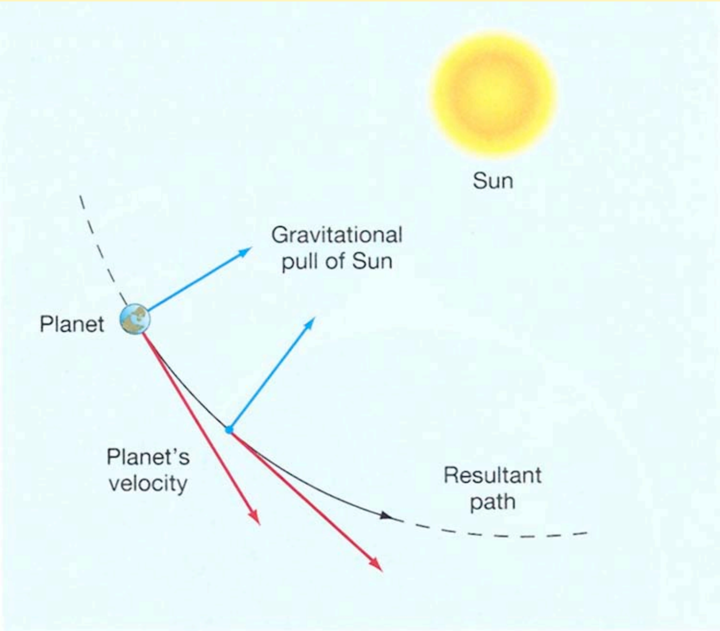


FIGURE 4.17 Moving the same mass at three different relative distances from the earth. For each distance, the thickness of the arrow indicates the relative amount of the gravitational force between the mass and the earth.



▲ **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 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 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. 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.

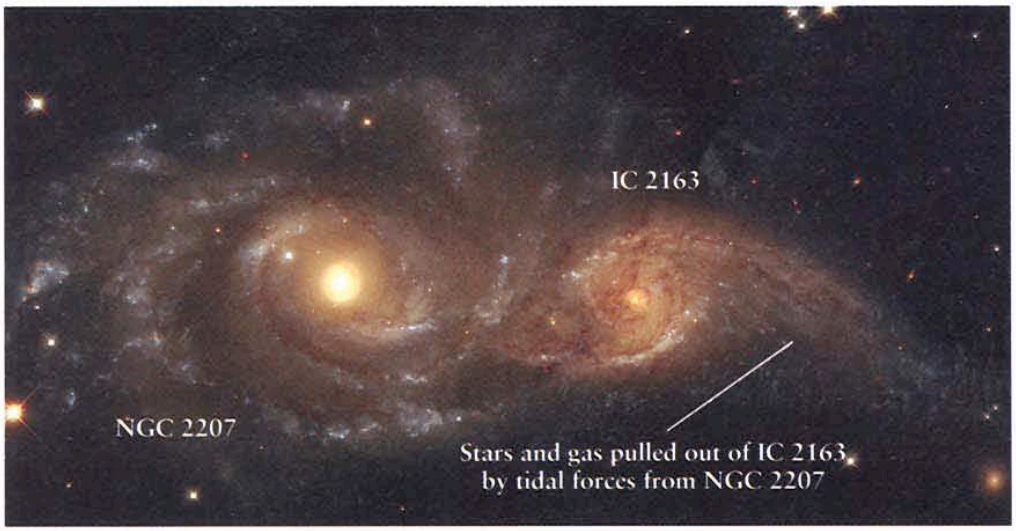


Figure 4-26 R I V U X G

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"(=3×10^5 km/sec = 2.86×10^5 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 $E = f \times c$

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:

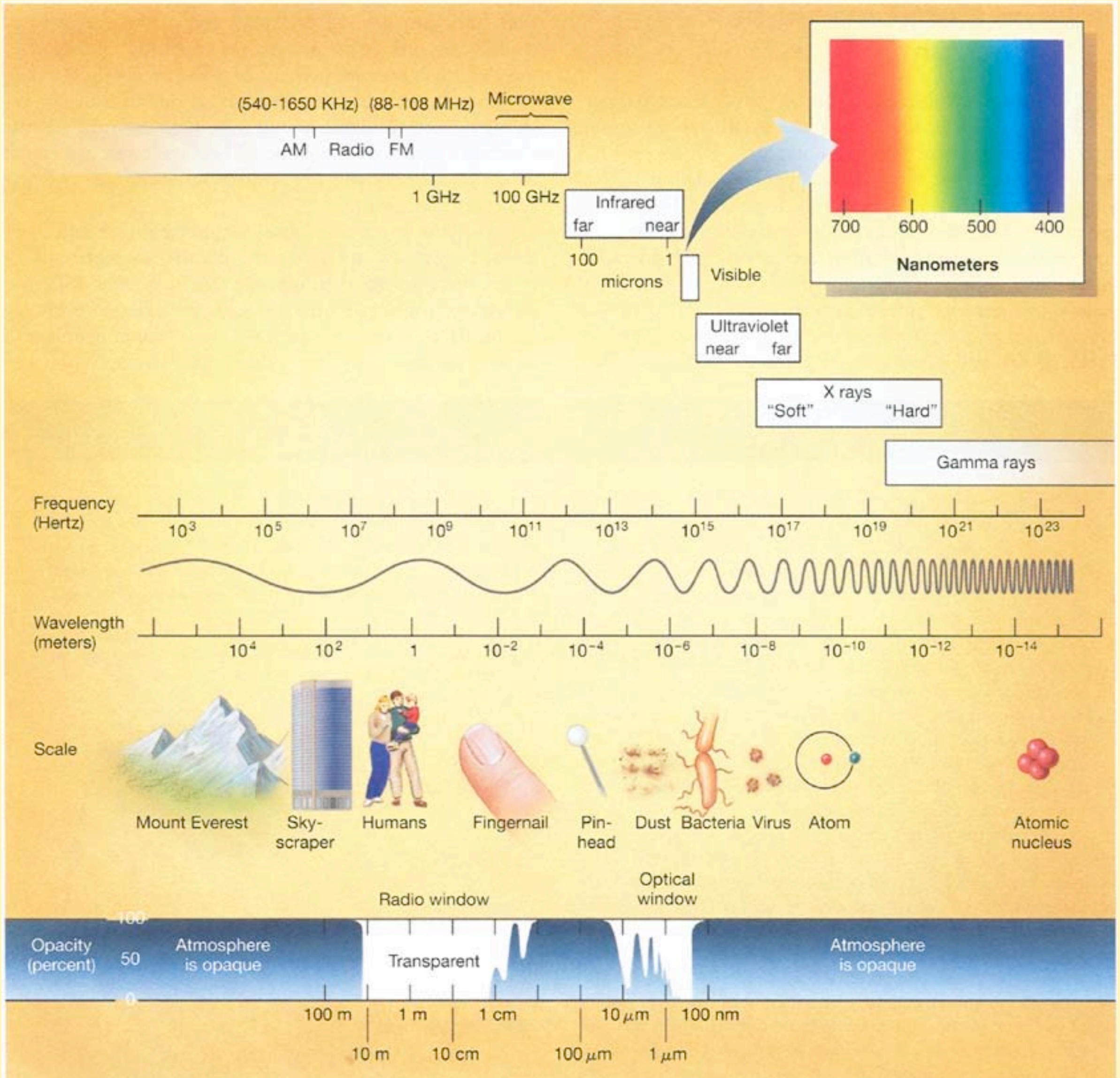
radio, infrared (IR), visible, ultraviolet (UV), x-rays, gamma rays

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.

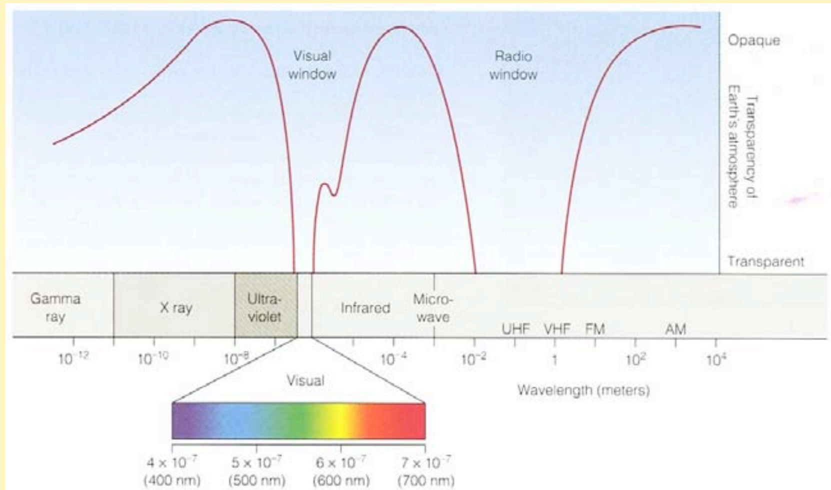


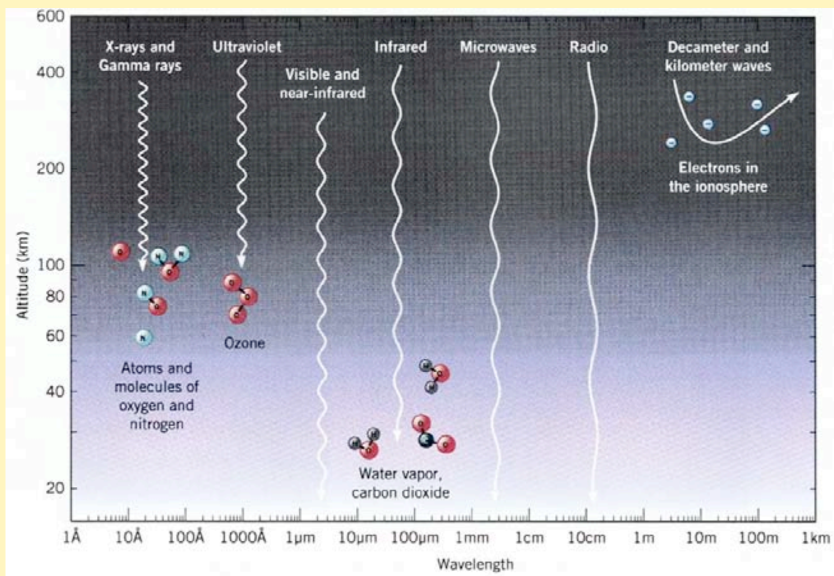
▲ **FIGURE 3.9 Electromagnetic Spectrum** The entire electromagnetic spectrum, running from long-wavelength, low-frequency radio waves to short-wavelength, high-frequency gamma rays.

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).