Chapter 5

STELLAR OBJECTS

A.) The Celestial Sphere:

1.) Some evening, go out into the desert or mountains--any place where city lights are non-existent--and look up. The night sky will be filled with tiny points of light--stars and galaxies, maybe the thickly lit inner section of our own galaxy, the Milky Way, maybe the occasional satellite zipping across the sky.

The question is, *how do we pin point where things are in the sky?*

2.) You and I know that the night sky has depth to it--that some stars are close and some far away--but the sky *looks* like a huge dome on which the stars are placed.

3.) This dome is called the *celestial sphere*.

a.) Observation #1: You *can't* tell how near or far something is on the celestial sphere by its brightness. Why? Because some objects are inherently brighter than others. An apparently bright object may be a small star that is very close, or a very large star that is far away.

b.) Observation #2: Celestial objects that are relatively near will appear to move over the celestial sphere. The moon, for instance, moves all over the place relative to more distant background stars on the celestial sphere.

c.) Observation #3: Due to their distance, celestial objects that are very far away do not appear to move very much at all. As a consequence, they seem stationary on the celestial sphere.

d.) Observation #4: Just to get a feel for size, a 1^o arc on the celestial sphere spans a distance that is about two moon diameters.

i.) In fact, a 1^o arc is also approximately the angle subtended when you view one pinkie at an arm's length.

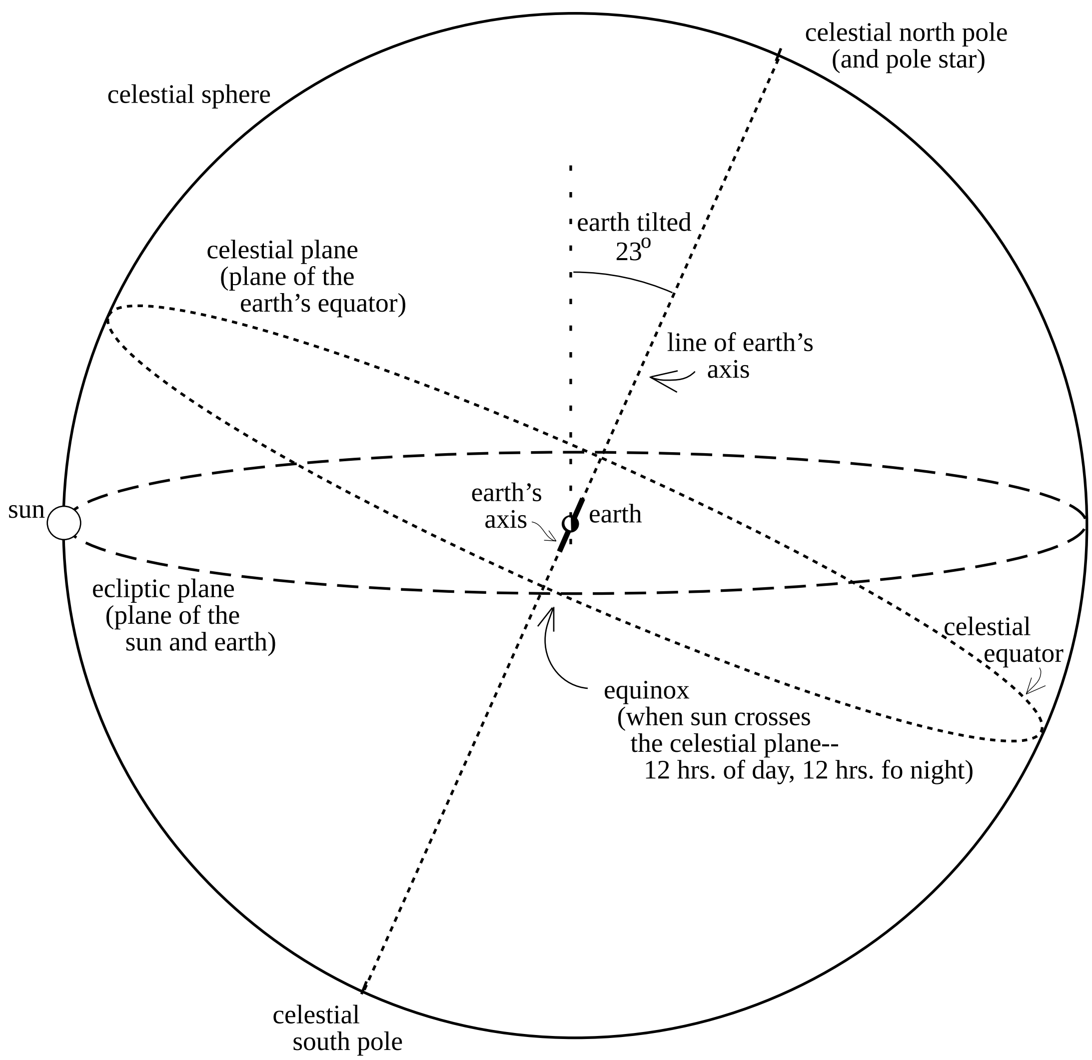
4.) It is possible to place a coordinate axis on the celestial sphere that locates where an object is at a particular point in time.

a.) When we project the earth's equator out onto the celestial sphere, we define what is called the *celestial equator*.

b.) If we project a line straight up from the earth's geographic north pole (i.e., by geographic pole, I mean the poles about which the earth rotates), we define what is called the *celestial north pole*.

i.) It is near this point that the *pole star*, which currently happens to be Polaris, resides.

CELESTIAL AND ECLIPTIC PLANE



c.) A line similarly projected down through the earth's south geographic pole defines the *celestial south pole*.

5.) Side point #1: The plane defined by the earth's orbit, called the *ecliptic plane*, does not lie on the plane defined by the *celestial equator*.

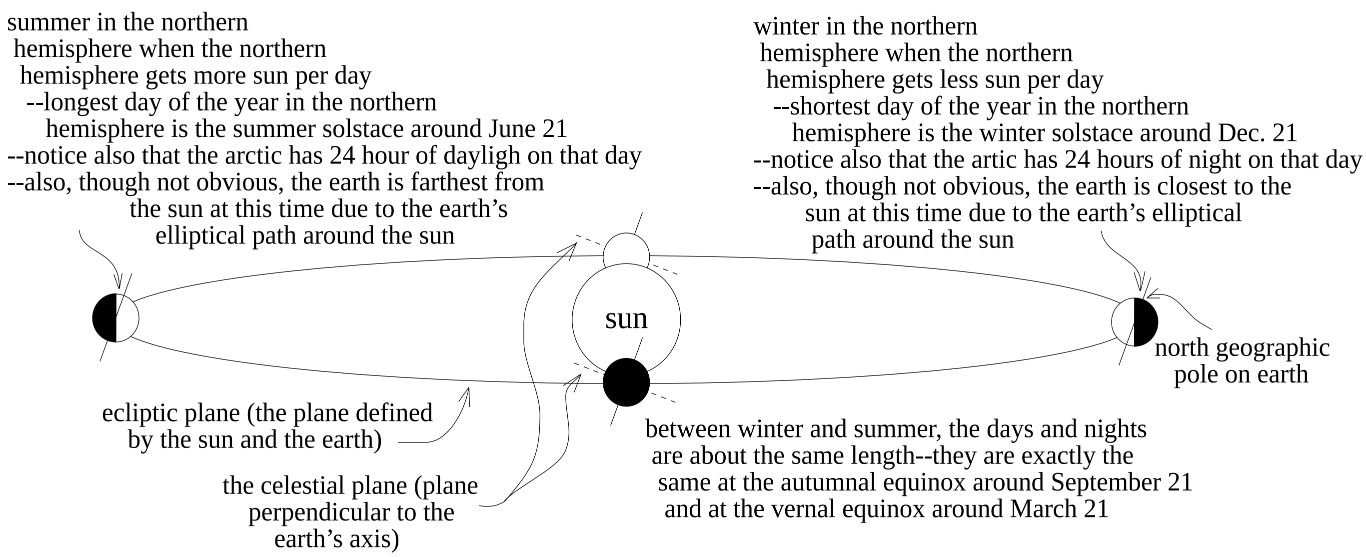
a.) In other words, the earth is tilted, relative to the plane of its orbit.

i.) This has been depicted on the sketch.

ii.) The tilt angle is 23.5^o.

6.) Side point #2: This tilt is why we have seasons. A quick check of the graphic will show why.

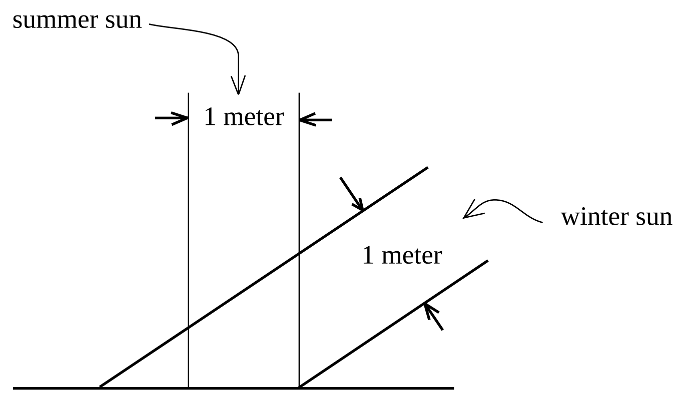
SEASONS



7.) Side point #3: The temptation is to look at the sketch above and assume that the reason that it is hotter in the summer is because the northern hemisphere is closer to the sun in the summer. This is *not* the case.

a.) In fact, due to its eccentricity (the earth's orbit is an ellipse), the earth is *farther* from the sun during the summer.

b.) So why is it hotter in the summer?



During summer when the sun is overhead, a lot of energy per unit area is absorbed by the earth. During the winter when the sun is coming in at an angle, the energy is more spread out as it hits the earth.

i.) The sun is higher in the sky--more northerly, more overhead in the northern hemisphere--during the summer.

ii.) Put a little differently, due to the tilt, the northern hemisphere has more *energy per unit area* impinge on it during summer than is the case during the winter when the sun is more to the south (i.e., lower in the sky). The sketch should help.

8.) Side point #4: The earth's tilt wobbles.

a.) It takes 26,000 years to complete one full cycle.

b.) This means the pole star changes periodically. Around 14,000 AD, Vega will be our pole star. In 26,000 years, the wobble will have brought us back to Polaris as our pole star.

9.) Side point #5: There are two times during the year when the Sun crosses the celestial plane, as seen from the earth. At that time, called the *equinox*, day and night occupy exactly the same amount of time (see previous graphics).

a.) The vernal equinox happens around March 21.

b.) The autumnal equinox happens around September 21.

10.) Side point #6: There are two times during the year when the sun is at its greatest angle, as seen on the earth, relative to the celestial equator. Near those times, collectively called the *solstice*, the longest and shortest days of the year occur. (It is not exactly at those times due to the eccentricity of the earth's orbit)

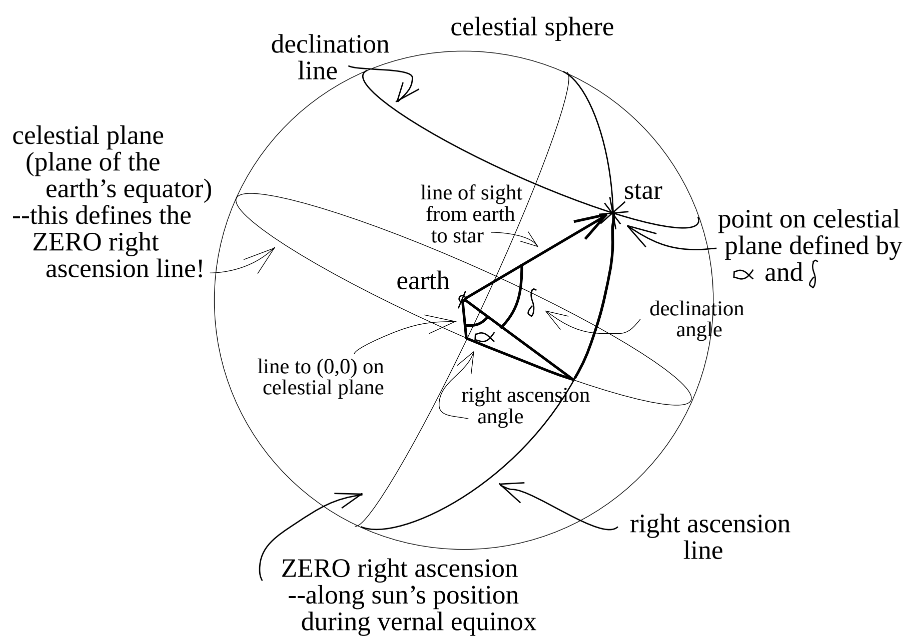
a.) The winter solstice is the shortest day in the northern hemisphere and the longest day in the southern hemisphere. It occurs around December 21. From the earth, this is the day the sun appears to be as far south in the sky as it will ever get.

b.) The summer solstice is the longest day of the year in the northern hemisphere and shortest in the southern hemisphere. It occurs around June 21. From the earth, this is the day the sun appears to be as far north in the sky as it will ever get.

11.) Back to the celestial sphere: Just as the earth has *longitude* lines that go *north* and *south*, the *celestial sphere* has what are called *right ascension* lines that go *north* and *south* on the celestial sphere.

a.) On earth, the *zero* longitudinal line is arbitrarily defined as going through Greenwich, England.

b.) The *zero* right ascension line on the celestial sphere is arbitrarily defined as going through the point on the sky occupied by the Sun at the *vernal equinox*. Right ascension is measured *easterly*.



12.) Just as the earth has *latitude* lines that are parallel to the equator, the celestial sphere has what are called *declination* lines that are parallel to the celestial equator.

a.) On earth, the *zero* latitude line is arbitrarily defined from the equator.

b.) The *zero* declination line on the celestial plane is arbitrarily defined at the celestial equator.

13.) In short, to find something on the celestial sphere, all you need to know is its *right ascension* and *declination*.

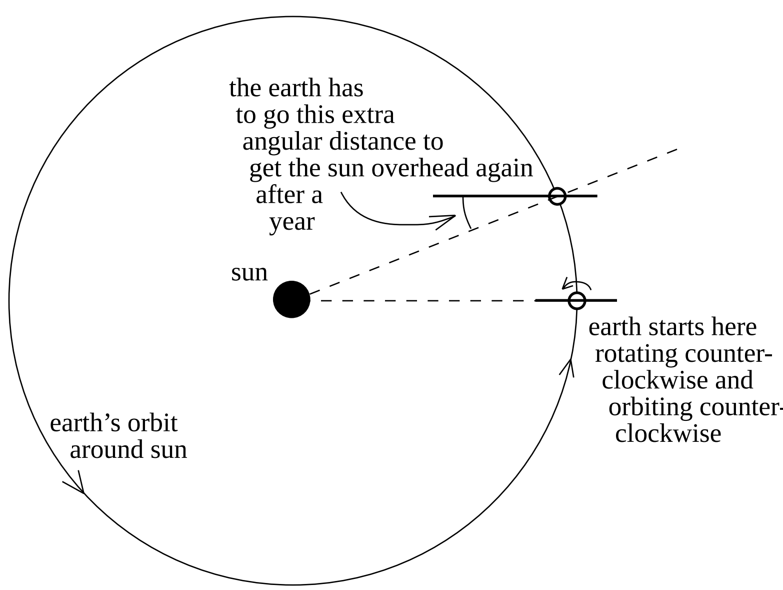
14.) So what is a solar day?

a.) A *solar day* is defined as the amount of time it takes from noon on one day (i.e., when the sun is directly overhead) to noon on the next day. It is determined by the rotation rate of the earth about its axis and the orbit of the earth around the sun.

Note 1: Because the earth is moving in an ellipse around the sun, the earth's orbital speed differs as the year proceeds. The "sun" that is referred to in the definition of the *solar day* is actually a fictitious "mean sun"--a kind of average positioned sun.

Note 2: As a consequence of this elliptical motion, the sun's position in the sky at *noon* every day will differ slightly. In fact, the pattern over the year looks like a *figure 8*. Called an *analemma*, this pattern is what has been placed on sun dials for centuries to make sun time and watch time match up. To see a very cool picture of this, go to *http://solar-center.stanford.edu/art/analemma.html.*

During a solar day, the earth rotates 360^o.



b.) There are 24 hours in a solar day. Because the earth will have traveled some distance in its orbit during a given solar day, the earth will rotate through *more than* 360 degrees in a solar day. In fact, it will rotate approximately 1 extra degree.

15.) What is a *sidereal* day?

a.) A *sidereal day* is defined as the amount of time it takes a star to pass the same point on the celestial plane as it appears to travel across the sky. It is determined solely by the rotation of the earth about its axis.

b.) A solar day is about four minutes longer than a sidereal day. Four minutes per day times 365 days is 24 hours. In other words, there is exactly one more sidereal day per year than solar day.

16.) What is a year?

a.) A year is defined as the amount of time it takes the earth to go around the sun once.

b.) The earth doesn't make a whole number of rotations about its axis in the time it takes the earth to go around the sun once.

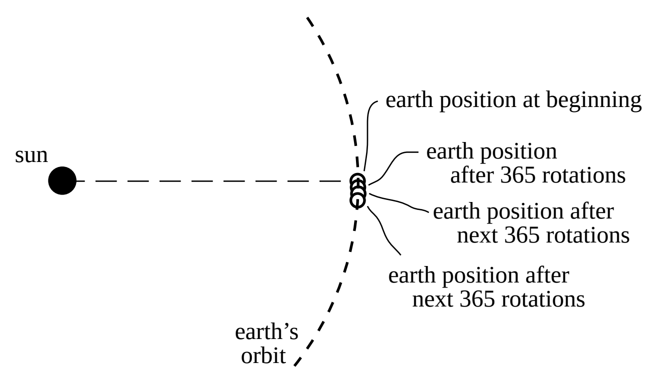
c.) In fact, it takes approximately 365.25 rotations, relative to the sun (this is *sun driven*, so it's associated with *solar time*), to go once around its orbit.

d.) As our calendar is *solar driven*, we have to deal with the fact that there are approximately .25 more rotations per orbital year than a 365 day solar year would accommodate.

17.) The problem with this extra bit of rotation is that if we did not make some kind of correction to our 365 day year, the seasons would slowly migrate away from their associated place on the calendar.

a.) If we waited 730 years, for instance,

Notice how earth's position, relative to the sun, migrates with each successive set of 365 rotations.



Christmas would be celebrated in the middle of summer.

b.) Additionally, when our calendars say it is somewhere around April or May, crops are usually planted. If we didn't make corrections to the calendar, it wouldn't take more than a few hundred years for crop planting time to happen when the calendar said February. This would be a huge inconvenience, at least for those who enjoy order and consistency in their world.

18.) The problem was remedied by Julius Caesar. He cut 90 days out of the "current" calendar (he did this in 46 BC) and instituted the idea of *leap year*.

a.) That is, the first three years of his calendar were normal (i.e., 365 days). The fourth year--leap year--had an extra day.

b.) The assumption was that if this pattern was repeated over and over again, the problem of migrating seasons would be solved and everyone would be happy.

19.) Unfortunately, the Julian calendar had a problem. It turns out that the extra bit rotation every year is not *exactly* .25 solar day's worth, it is closer to .24's worth. So by 1582, the calendar was again out of sync, this time by 10 days.

a.) At that point, Pope Gregory came up with what is known as the Gregorian calendar.

b.) This was similar to the Julian calendar in the sense that it has a leap year every four years, but every 100 years the leap year is skipped . . . except every *400 years* when it was put back in again. Confusing, yes. A better calendar, yes also.

c.) When the calendar was introduced, riots broke out in the streets over the lost 10 days.

20.) As surprising as this might be, England and America didn't accept the new calendar until 1752 (England was Protestant and not at all interesting in following the Pope's lead).

a.) By that time, 12 days had been lost. So when the change-over took place, Wednesday, September 2, 1752 was followed by Thursday, September 14, 1752.

b.) Again, there was rioting in the streets over the "lost" days.

c.) Interesting side note for those of you who have an urge to become historians: Before England and the colonies made the change, the New Year started on March 25 in England and the colonies. After the Gregorian calendar was adopted, New Years fell on January 1.

i.) One of the bits of amusement that comes out of this is that if you happened upon the records of George Washington's birth, written when the Julian calendar was still in use, they would tell you that he was born on February 11, 1731. It wasn't until the Gregorian calendar came into effect that we placed his birth on February 22, 1732.

ii.) The point: There are all sorts of way to get messed up when you are trying to research historical information when using source material that was written several hundred years ago.

d.) Fortunately, for you patriots who are embarrassed by the fact that it took the colonies almost 200 years to realize that their accepted calendar was messed up, it is possible to take solace in the fact that:

i.) The Russians didn't accept the new calendar until 1918. (That means Alaskans didn't accept it until 1867 when Alaska was transferred from a Russian to a U.S. territory.)

ii.) The Japanese didn't transfer until 1873 after their first contact with Europeans.

iii.) And China didn't change until 1949 when the communists took over. (Evidently the communists did *something* right.)

B.) Light From a Star:

1.) When we are dealing with a star, there is data that is easily obtained and there is information that is not so easily obtained but that we would like to know, anyway. This section is designed to identify what belongs in each category. When we get done doing the identifying, we'll look at the physics we have available to answer the questions.

2.) First, what information can we gather by looking at the light a star gives off?

a.) We will have the opportunity to capture all of the frequencies of electromagnetic radiation that make up the light from the star. A corollary to this is that we should be able to tell the color of the star.

b.) We should be able to tell the apparent brightness of the star.

c.) We should be able to tell where on the celestial sphere the star is and, if we wait a half a year, where the star is on the celestial sphere is at that second point in time.

i.) That is, if the star is close, it will appear to have moved relative to the celestial plane. We will, for the sake of argument, assume the stars we are looking at for now are close.

3.) Second, what kind of information are we interested in determining about our star?

a.) How big is the size (i.e., what is its radius).

b.) How far away is the star?

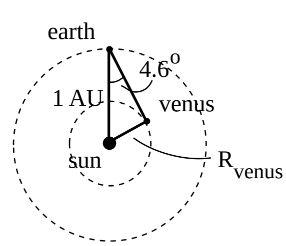
c.) What is the mass of the star?

d.) What is the star made of?

4.) So much for the questions. Now for the physics.

C.) Distances to Relatively Near Celestial Objects:

1.) There is information that can be determined using nothing more than a protractor and geometry.



a.) Example: The distance between the earth and the sun is *one astronomic unit* (i.e., *1 AU*). As observed from the earth, the maximum angle Venus achieves, relative to the sun, is 4.6^o (see sketch).

b.) As the *sine* of an angle is equal to opposite side (in this case, the radius R_V of Venus's motion around the sun) divided by the hypotenuse (in this case, the earth's rotational radius, or 1 AU), we can write $R_V = (1\ AU)(\sin 46^o) = .72\ AU$.

c.) Evidently, the radius of Venus's orbit around the sun is .72 times the radius of the earth's orbit.

2.) The easiest current way to get the distance between the earth and the planets (in kilometers) is to bounce radio waves off them and see how long it takes the return wave to get to earth. All of the planetary distances can be determined in this way. For example:

a.) The shortest earth-Venus round trip takes 4.5 minutes (this is 270 seconds--it corresponds to when Venus is *closest* to the earth). That means it takes the signal 135 seconds to make the trip one way.

b.) The distance an object travels equals its speed times the time it takes to do the traveling (this is the old *distance equals rate times time* formula you probably learned some time back).

c.) The distance between the earth and Venus is, therefore

$$\begin{aligned} d_{\text{earth to venus}} &= (ct) \\ &= \left(3\text{x}10^8\ \text{m/s}\right)(135\ \text{sec}) \\ &= 405\text{x}10^8\ \text{meters} \\ &= 2.5\text{x}10^7\ \text{miles.} \end{aligned}$$

d.) This number isn't important--don't memorize it--but knowing how you got the number is important.

e.) Because the sun hasn't a hard surface, using radio waves won't work on it. With the information determined above, though, we can determine the distance between the earth and sun. Specifically,

$$d_{\text{earth to sun}} = \frac{\text{distance of venus to sun}}{\text{ratio of distance between earth and sun and venus and sun}}$$

$$= \frac{4 \times 10^{10}\ \text{m}}{1 - 0.72}$$

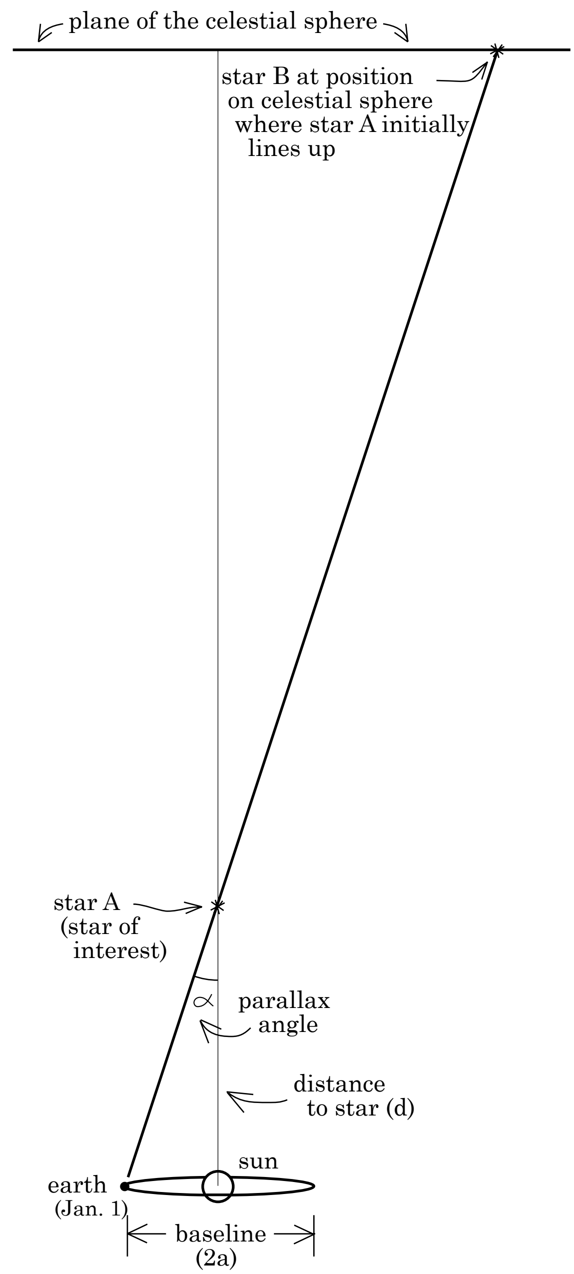
$$= 1.5 \times 10^{11}\ \text{meters}$$

$$= 93 \times 10^{6}\ \text{miles.}$$

3.) The radar technique really only works inside the solar system. Why? Because radio waves thin down as they move outward. We could bounce them off objects that are several light years away, but the returning signal would be so weak that we would not be able to detect it. For objects that are not terribly far away, there is another approach that uses the idea of *parallax*.

4.) What is parallax? Close one eye and view your index finger held out at arms length. Notice where on the opposite wall your finger appears to rest. Now shut that eye and open the other. The apparent position of your fingers, relative to the wall, has changed. This apparent shifting of position against a distant backdrop is called *parallax*.

5.) To use *parallax*, we need to sight the object in question--let's assume it is *star A*--from two positions. Because stars are still a long way away--our nearest star neighbor, Alpha Centauri, is 4.3 light years away--we need as wide a baseline between the observation points as possible. In fact, the base line used in astronomy is twice the distance from the earth to the sun. That is, it is the distance between the earth's position at one point in time during the year, and the earth's position six months later.



6.) How does this work?

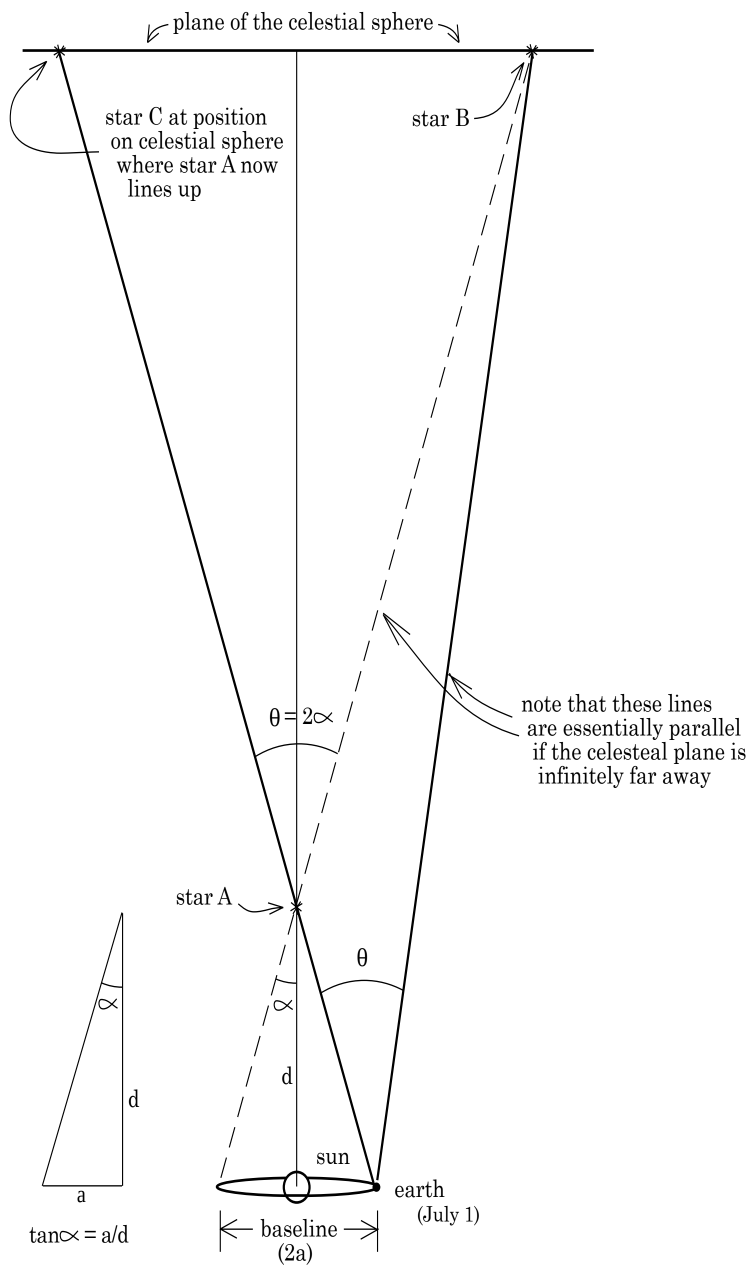
a.) On, say, January 1, *star A* is sighted and its position on near a very far star or quasar on the celestial sphere is noted. For the sake of argument, let's assume that reference star is *star B*. That situation is shown in the first sketch on the previous page.

b.) On July 1, *star A* is again observed. Where it appears to reside on the celestial sphere is again noted, as shown on the second sketch.

c.) The angle θ in that sketch is measured using the fact that the distance between any two points on a photographic plate is equal to the focal length of the telescope gathering the light *times* the angle (in radians) subtended by the arc between the two points in the sky (this is a little obscure, but it happens to be true). In other words, θ is measurable.

d.) Half of θ, called the *parallax angle*, is denoted by an α.

e.) From trig, we can determine the distance d to the star using the relationship $tan\ \alpha = d/a$, where a is the distance between the earth and the sun (i.e., half the base line).



f.) This technique works just fine as long as the object of interest doesn't subtend an angle that is too small to measure, and as long as *star B* and *star C* are very, very distant.

7.) We have just defined *distance* in terms of a parallax angle. We could express that distance in light years, or we could be clever and simply express it in terms of the parallax angle itself.

a.) *Parallax in arc seconds*, or the *parsec*, is defined as the distance associated with a parallax angle of one arc second.

b.) *One parsec* is numerically equal to 3.3 light years.

8.) If your eyes were far apart, you would get a natural parallax. A Web page that alludes to this shows stereo images of Hipparcos parallax data (Hipparcos was an experiment done several years ago to track the motion of stars). It is at http://astro.estec.esa.nl/Hipparcos/3dstereo_images.html

D.) Black Body Radiation, Energy Flux, and Luminosity:

1.) Remember back when we talked about optical light being produced when an electron transit from one energy level to another energy level in an atom? Well, aggregates of bonded atoms--molecules--have specific energy levels associated with *their* structure, also. And just like atoms, they are constantly absorbing and emitting energy by transiting from one of those energy states to another. In short, *all objects* radiate energy over a spread of electromagnetic frequencies.

2.) A graph of this spread is called the *black body radiation curve*.

a.) The shape of the *black body radiation curve* looks the same for all objects, but where the curve lands along the frequency axis depend *solely* on the radiating object's temperature.

b.) In other words, the frequency at which the radiation peaks, called the *peak frequency*, is dependent upon the object's temperature. Mathematically, this yields

$$\nu_{peak} \propto T.$$

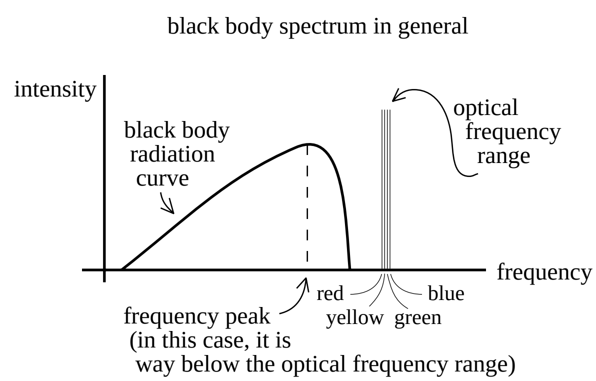
c.) As a side point, the proportionality constant for this relationship is 10^{11} sec^{-1}. That means we could write it as $\nu_{peak} = 10^{11}\,T$ *(Hertz)*, where *T* is temperature in *degrees Kelvin*.

d.) As another side point that will come in handy later, we can also write this as a wavelength. Remembering that the relationship between frequency and wavelength is $c = \nu_{peak}\lambda_{peak}$, where *c* is the speed of light, the peak wavelength associated with this peak frequency is equal to

$$\lambda_{peak} = \frac{.0029 \text{ meters}}{T}.$$

2.) A *energy flux* in general is defined as the amount of *energy* that passes through a surface *per unit area per unit time.*

Note: Shortly, we will look at the energy flux of a star as measured on the star's surface. Later, we will look at the energy flux of a star as measured on the earth where the value will be much, much less than on the star's surface.



a.) The unit for *energy flux* is *joules/second/m*^{2} in the MKS system, or *Watts/m*^{2} if you want to get fancy.

b.) We know from experimentation that the energy flux from a radiating object is proportional to the fourth power of the object's surface temperature as measured in degrees Kelvin. The proportionality constant, called the *Stefan-Boltzman constant*, is symbolized as σ. Using this, we can present a star's energy flux as

$$F = \sigma T^4.$$

Note: All of this is logical. It makes sense that the hotter an object, the more energy it will give off. All it took was a little experimentation to determine the relationship between *energy released* and an object's *temperature*.

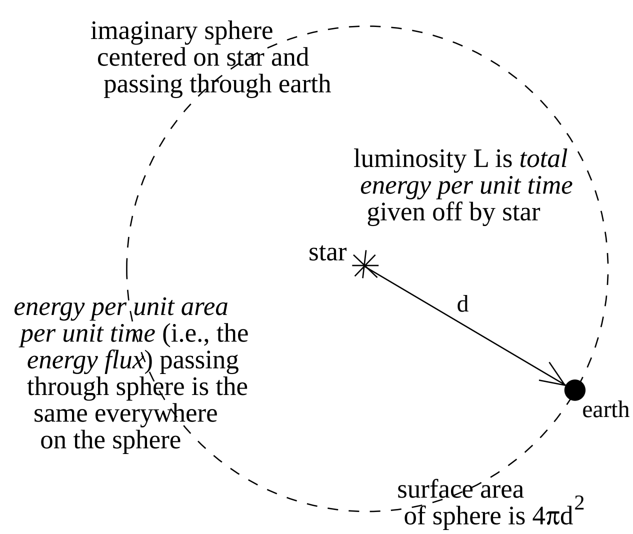
3.) A star's *luminosity* is defined as the total amount of *energy* from all frequencies of radiation and in all directions given off by the star *per unit time*.

a.) A star's *luminosity* is equal to the star's surface *energy flux* times the *surface area* of the star.

b.) How so? The *energy flux* tells you how much *energy* is being dumped *per unit area per unit time*. If you multiply that by the total *area* of the star, you are left with the amount of *energy* being dumped *per unit time*. This is the luminosity. Noting that the surface area of a spherical star is $4\pi R^2$, where R is the sphere's radius, we can write the luminosity relationship for a star as

$$\begin{aligned} L &= (\text{energy density})(\text{star's surface area}) \\ &= \quad (\sigma T^4) \qquad\qquad (4\pi R_{star}^{\ 2}). \end{aligned}$$

c.) Notice that if we can determine the star's temperature and luminosity, we can determine its radius. (We'll get to determining a star's luminosity shortly.)



apparent brightness (i.e., energy flux at earth) equals (star’s luminosity)/(sphere’s surface area), or $F = L/(4\pi d^2)$

4.) We can also determine the distance to a star if we know the star's *luminosity*.

a.) Any surface that has energy passing through it has an energy flux associated with it. So let's say we are trying to determine the distance between a star and the earth.

b.) Imagine the earth sitting on a sphere that is centered at the star.

c.) The energy flux through that sphere (i.e., the amount of energy that passes through the sphere *per unit* *area* per unit time) will equal the total amount of energy coming out from the star per unit time (this is the luminosity) divided by the area of the sphere. In other words,

$$F_{\text{at surface}} = \frac{(\text{energy per unit time through sphere})}{(\text{sphere's area})}$$

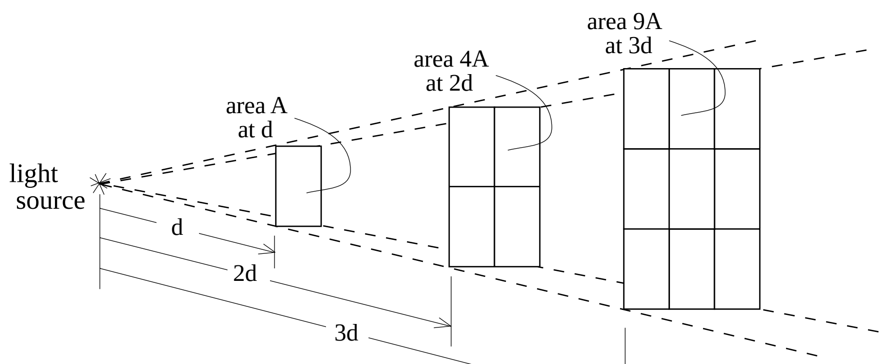
$$= \frac{L}{4\pi d^2}.$$

d.) As the earth is on the sphere, we can measure the energy density on the sphere generated by the star's light. How? We can look at the star with a telescope, direct its light onto a photosensitive surface, measure the amount of energy that impinges on that surface per second, then divide by the area of the photosensitive surface to determine the amount of *energy per unit area per unit time* . . . which is to say, the energy density as measured on earth.

e.) Minor but important note: Another name for energy flux in this case is *apparent brightness*. That is, whenever you hear the term *apparent brightness*, think *energy*.

Note: What we have just done has been to justify what is called the *inverse square law*. That "law" states that light intensity (i.e., apparent brightness or energy flux or whatever you want to call it) drops off as the square of the distance from the source. In other words, $F \propto \frac{1}{d^2}$. This can be easily seen in the graphic.

f.) With $F_{at\ earth}$ and L, we can determine the distance d to the star. The only hang-up is getting the luminosity L.



In general, the area enclosed by the dashed lines is proportional to the square of the the distance *d* from the source. As the energy per unit time inside the dashed lines doesn't changed even though the area does, the energy *per unit time per unit area* (i.e., the apparent brightness) changes as the inverse of the distance *d* from the source squared.

5.) So how, today, do we determine a distant star's luminosity?

a.) If you can find a star that is close and that has the same color and light spectrum as the star of interest, you have it made. How so?

b.) You can use parallax to determine the distance d to the near star.

c.) You can measure the *apparent brightness* (again, this is the energy flux F as measured on earth) from the near star.

d.) With the star's distance and apparent brightness, you can use the relationship

$$F = \frac{L}{4\pi(d_{nearstar})^2}$$

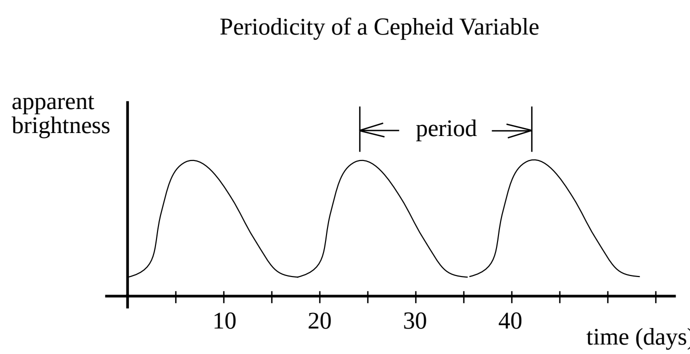
to determine the near star's luminosity as

$$L = F\left[4\pi(d_{nearstar})^2\right].$$

e.) Stars have a relatively well understood life path during which they do very specific things at very specific points in that life. Finding a second, near star that has the same color, spectral lines, and spectral broadening as the *star of interest* means you have found a star that is at least very close to being identical to the *star of interest*. In other words, knowing the luminosity of the near star gives you a pretty good estimate of the luminosity of the more distant star.

E.) Standard Candles and Variable Stars:

1.) Under the right conditions during stellar evolution, it is possible for a star to go through a period of time when its size and luminosity vary. Called *variable stars*, there are two types of interest. They are Cepheid stars and RR Lyrae stars. (We'll just talk about Cepheids.)



2.) Cepheid variables are fairly massive stars whose luminosity and radius changes in a periodic way. How does it do this? It has to do with changes in the star's opacity (i.e., ability to leak radiation out from the core).

a.) In normal stars, there is a balance between the outward pressure of the star's gas (heated by the fusion process at the star's core) and the inward pull of gravity. The star is thus in static equilibrium.

b.) Stars don't necessarily start out in that state, though. Gravity forces material to compress until nuclear fusion is ignited. At that point, heat produced by the fusion process stops the gravitational collapse and, in fact, pushes the material outward beyond equilibrium until gravity takes over again.

i.) Under normal conditions, the oscillation between being too compressed and not being compressed enough is relatively short lived.

ii.) That is, friction eventually dampens out this in-and-out oscillation in normal stars, just as the motion of a kid on a swing dampens out if the kid doesn't pump to keep the swinging going.

iii.) How does this damping really work? When the star is compressed, it heats up. With the high temperatures, the star's atoms have their electrons stripped from them. In that state, the atoms become smaller "targets" and, as a consequence, radiation in the form of heat energy is able to leak out from the star faster than normal. This, in turn, decreases the gas pressure that makes the star rebound, and so dampens the oscillation.

c.) What makes Cepheid stars different?

i.) It turns out that in Cepheids, the temperature at a particular layer inside the star is just right so that compression of the gas in that layer doesn't make the layer *less* interactive with the radiation leaking from the core (as explained in part b-iii above), it makes the atoms MORE interactive with the radiation leaking out of the core of the star.

ii.) In other words, this layer *slows* the leakage of radiation trapping heat energy in the star and *increasing* the gas pressure even more.

iii.) This increase pushes the star out even faster than on the last cycle (this is like a kid on a swing who is pumping to make the oscillation grow and grow).

iv.) Of course, the other layers of the star are acting normally, trying to dampen the oscillation that builds up. But with that one renegade layer, the oscillation doesn't dampen out as expected of "normal" stars and the amplitude of the oscillation becomes relatively constant.

v.) Consequence: Cepheid oscillates proceed back and forth until it runs out of nuclear fuel.

d.) In general, the frequency of Cepheid oscillations can be anywhere from *one* to a *hundred* days.

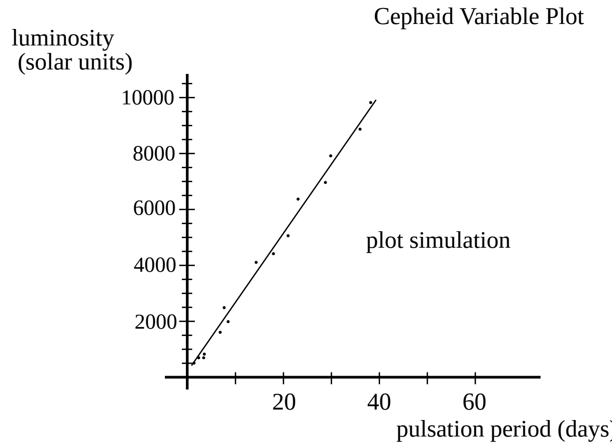
3.) What is useful about these stars is that the *frequency* of their variation in luminosity has been found to be related to the *average luminosity* itself.

a.) A Cepheid whose apparent brightness changes very fast (i.e., whose *period* of pulsation . . . whose time to do one pulse . . . is short) is relatively low in average luminosity.

b.) A Cepheid whose apparent brightness changes slowly (i.e., whose period of pulsation is long) has a relatively high average luminosity.

4.) How do we know this is true?

a.) If we can find a bunch of Cepheids that are all about the same distance away (i.e., say, Cepheids in the Large Magellanic Cloud--a satellite galaxy of the Milky Way), you can plot their *apparent brightness* versus *pulsation period* to get an uncalibrated graph. That is, you will know the relative relationship. You just won't have a luminosity scale to go with the plot.



b.) What is nice is that there is exactly *one* Cepheid within 3000 light years of us. That means we can determine its distance using *stellar parallax*, measure its apparent brightness, determine its luminosity, and put that luminosity on our graph. With that, we will be able to scale the rest of the axis and our Cepheid plot will be complete.

c.) As all Cepheids in other galaxies act in accordance with this plot, it's a good bet that if we find a new Cepheid somewhere, it will act just like the ones we already know about. In other words, if we find a distant Cepheid and want to know its luminosity, all we have to do is measure its pulsation rate, then look on the plot.

d.) Consequence? One way to find the distance to other galaxies is to find a Cepheid variable in the galaxy of interest, measure its pulsation rate to determine its luminosity, then use its average apparent brightness to determine the distance to that star, hence galaxy. Clever, eh?

e.) A Web source for light samples from Cepheids in the Magellanic Cloud is at http://adsabs.harvard.edu/cgi-bin/nph-data_query?bibcode=1995AJ....109.1653A&link_type=ARTICLE&db_key=AST (Alcock et al 1995 AJ 109, 1653) . . . see Figure 1 and Figure 5.

5.) Although we won't talk about supernovas until next chapter, it turns out that there is one class of supernova that can also be used as a *standard candle* for determining luminosities and, from that, distances. We will talk about it later.

F.) Some Examples:

Note: The numbers we are about to determine in these examples are *not* important. What is important is how we got the numbers.

1.) Example Problem 1: Consider our star, the sun. Its surface temperature is approximately 6000 degrees Kelvin (it's actually 5777 degrees Kelvin, but 6000 will do for our purposes). What can we deduce from its black body curve. Specifically:

a.) What is its peak wavelength?

b.) What frequency corresponds to that peak wavelength?

c.) What does its *black body radiation curve* look like (a general sketch will do)?

d.) As an off-the-wall side excursion, how much energy does a photon at that peak frequency carry? (Kindly note that Planck's constant is 6.626×10^{-34} joules·seconds.)

e.) There are 1.6×10^{-19} joules/ electron-volt. How many eV's of energy do photons carry at peak frequency?

f.) What's the sun's *energy flux*?

g.) What's the sun's *luminosity*?

2.) SOLUTIONS to *Example Problem 1*.

a.) The peak wavelength of the sun will be

$$\lambda_{peak} = \frac{.0029 \text{ m}}{6000}$$

$$= 4830 \times 10^{-10} \text{ m}$$

$$= 4830 \text{ Å}.$$

i.) Minor Note: This is the wavelength for *cyan light* (i.e., blue/green light). The reason the sun doesn't look bluish to us is because our eyes are not very sensitive to the blue end of the spectrum.

b.) We can get the peak frequency in one of two ways.

i.) In the first way, we simply take the peak wavelength and divide it into the speed of light. That is, we can take $c = \lambda_{peak} \nu_{peak}$ and solve for ν_{peak}. Doing so yields:

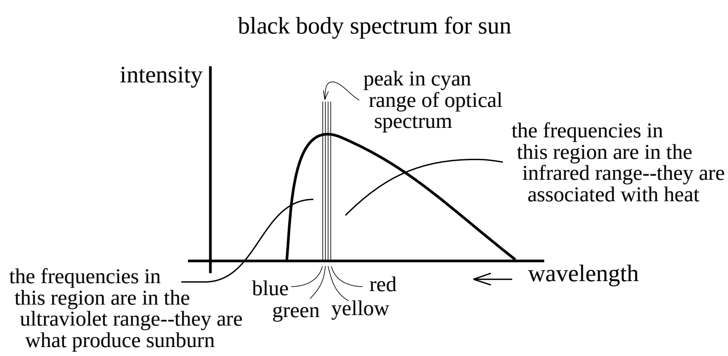
$$\begin{aligned} c &= \lambda_{peak} \nu_{peak} \\ \Rightarrow \nu_{peak} &= \frac{c}{\lambda_{peak}} \\ &= \frac{3 \times 10^{8}}{4830 \times 10^{-10}} \\ &= 6.2 \times 10^{14} \text{ Hz.} \end{aligned}$$

ii.) The second alternative is to use the relationship we have for peak frequency straight away. That is:

$$\begin{aligned} \nu_{peak} &= 10^{11} T \\ &= 10^{11}(6000) \\ &= 6 \times 10^{14} \text{ Hz.} \end{aligned}$$

Note: The values determined using the two approaches are not exact due to round-off error and the approximations used. They are, nevertheless, in the ball park.

c.) A general sketch of the *black body radiation curve* will look like *all* black body radiation curves. What will make is specific to this situation is where its peak is located. In this case, as was pointed out above, it will be located where the *cyan* (i.e., blue/green) line of the optical range is located. The sketch is shown to the right.



d.) The amount of energy *any* photon carries is related to the frequency of radiation associated with the photon. That relationship is $E = h\nu$, where h is Planck's constant and ν is the frequency. At the peak frequency, this is

$$\begin{aligned} E &= h\nu \\ &= \left(6.626\text{x}10^{-34} \text{ joule} \bullet \text{seconds}\right)\left(6.2\text{x}10^{14} \text{ cycles / second}\right) \\ &= 4.2\text{x}10^{-19} \text{ joules.} \end{aligned}$$

e.) As there are $1.6\text{x}10^{-19}$ joules per electron-volt, $4.2\text{x}10^{-19}$ joules of energy comes out to 2.6 eV per photon.

Note: This is on par with the binding energy of atoms and molecules like the melanin in your skin (it produces skin tone), and the chemicals in photographic film, blue print paper, and dyes and paints. That is why paints fade in sunlight. The sun's photons are energetic enough to break dye molecules apart.

f.) The *energy flux* of a star is related to the fourth power of the star's surface temperature. Using the *Stefan-Boltzman constant* (i.e., $\sigma = 5.67\text{x}10^{-8}\ W/(m^2)$) to present this as an equality, we can write

$$\begin{aligned} F &= \sigma T^4 \\ F &= \left(5.67\text{x}10^{-8} \text{ W / m}^2\right)\left(6000 \text{ K}\right)^4 \\ &= 7.3\text{x}10^{7} \text{ W / m}^2. \end{aligned}$$

Note 1: It may appear that these are the wrong units. After all, *energy flux* is supposed to be *energy per square meter of surface per second.* In fact, though, *watts* (symbol *W*) is a measure of *power*, which is a measure of *energy per second*. In fact, you run into *watts* every day in your home. A 150 Watt light bulb dissipates 150 joules of energy every second. The point is that our answer *could* as easily have been written as $7.3\text{x}10^7$ (joules/sec)/m^2, which is the same as $7.3\text{x}10^7$ Watts/m^2.

Note 2: Remember, *degrees Kelvin* is a generic quantity and not a unit. So although I have included it with the 6000 in the problem above, I could as easily have just written 6000 without units.

g.) The *total energy* given off by the sun's surface *per second* . . . which is to say, its *luminosity* . . . is *FA*, where *F* is its energy density and *A* is the surface area of the sun (i.e., $4\pi r^2 = 4\pi(7x10^8\ m)^2 = 6x10^{18}\ m^2$--I've rounded off, so this is approximate). The luminosity is, therefore,

$$\begin{aligned} L = &\quad F \qquad\qquad A \\ &= (7.3\text{x}10^7\ \text{W/m}^2)(6\text{x}10^{18}\ \text{m}^2) \\ &= 4.4\text{x}10^{26}\ \text{joules/second.} \end{aligned}$$

Note: A joule is about the amount of energy you would have to expend to raise a three-quarter pound object up one foot.

3.) Example Problem 2: A warm rock might have a temperature of around 100^o F (this is approximately 37^o C or 310^o K). What is the deal with the radiation *it* gives off? Specifically:

a.) What is the peak frequency of its black body radiation curve?

b.) What does its black body radiation curve look like?

c.) How much energy do photons at the peak frequency carry?

d.) What is the rock's energy flux?

e.) Let's assume the rock's form is that of a 10 cm by 10 cm by 10 cm cube (that's about 5 inches on a side). How much total energy does the rock give off per second?

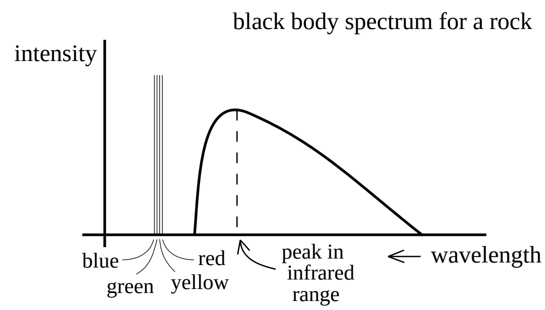
f.) If you happened to feel all of the heat from one face of the cube, and if all of that heat was produced by photons at the peak frequency (it wouldn't be, but if it was), how many photons would be hitting your hand per second?

4.) Solutions to *Example Problem 2*:

a.) The peak frequency from our rock's black body radiation curve is

$$\nu_{peak} = 10^{11} T$$
$$= 10^{11}(310)$$
$$= 3.1 x 10^{13} \text{ Hz.}$$

b.) This frequency is below that of optical light and is in the infrared range. (It corresponds to a wavelength of 94,000 Å--around the thickness of a human hair.) The corresponding black body radiation curve is shown in the sketch.



c.) The energy carried by each photon at this peak frequency is

$$E = h\nu$$
$$= \left(6.626 x 10^{-34} \text{ joule} \bullet \text{seconds}\right)\left(3.2 x 10^{13} \text{ cycles / second}\right)$$
$$= 2.1 x 10^{-20} \text{ joules.}$$

This is the energy equivalent of each photon carrying around .13 eVs of energy.

d.) As for total *energy* given off *per area per unit time*, the energy flux for the rock will be

$$F = \sigma T^4$$
$$F = \left(5.67 x 10^{-8} \text{ W / m}^2\right)(300 \text{ K})^4$$
$$= 460 \text{ (joules / sec) / m}^2.$$

e.) What you are really being asked for here is *luminosity* (look at the units!). If you know the energy flux and the total area of the cube, the luminosity will simply be the energy flux times the area.

Each side of the cube has the dimensions 10 cm by 10 cm. That means each side has an area of .01 meters^2. The energy flux is 460 j/s/m^2, so multiplying the two will yield the energy dumped by *one side* of the cube *per second*. But there are *six sides*, so the total energy will be

$$\begin{aligned} L &= \quad F \qquad\qquad A \\ &= (460\ W/m^2)[6(.01\ m^2)] \\ &= 27.6\ \text{joules/second.} \end{aligned}$$

f.) (This is very off the wall.) If the total energy emitted by the cube is 27.6 joules, the energy emitted by one face must be 4.6 joules. If you absorbed all of the energy from that one side, and if it all came at you via photons at peak frequency, there would be

$$(4.6\ \text{joules})/(2.1\text{x}10^{-20}\ \text{joules/photon}) = 4\text{x}10^{19}\ \text{photons}$$

hitting your hand every second. In other words, somewhere in the vicinity of 40,000,000,000,000,000,000 photons would strike your skin every second.

5.) Example Problem 3: Assume your parents have given you ten minutes of time on the Hubble space telescope. (This would cost around $100,000, assuming you could find a 10 minute period when it wasn't spoken for.) You spot a star you think looks sexy, you sweep through the infrared, optical, and ultraviolet ranges of the electromagnetic spectrum of the star, and you find its peak frequency is 6.2x10^{15} Hz.

a.) What wavelength corresponds to this frequency, and where is it on the electromagnetic spectrum (that is, is it in the microwave range or the ultraviolet range or the radio frequency range or what)?

b.) What does the *black body radiation curve* look like for this star?

c.) What is the star's temperature?

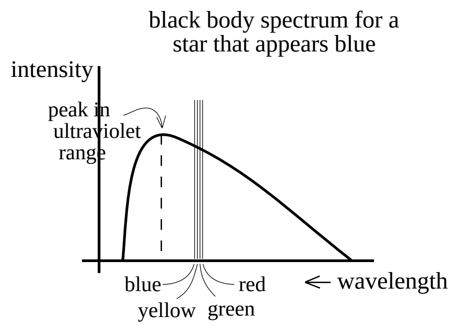
d.) What is the star's energy flux?

e.) Why would you need the Hubble space based telescope to deal with this star? (This is a little off the wall, but it identifies an important point.)

6.) Solutions to *Example Problem 3*.

a.) Using $c = \lambda_{peak} \nu_{peak}$, the wavelength associated with this frequency is 480 angstroms. This corresponds to electromagnetic radiation in the ultraviolet range.

b.) The black body radiation curve for this star is shown in the sketch.



c.) You can determine the star's temperature either by using the wavelength relationship quoted above or by using the frequency relationship. Either will do. I have used the relationship you have for peak wavelength, which is to say $\lambda_{peak} = \frac{.0029\ m^2}{T}$. (Try checking it with the frequency relationship.)

$$\lambda_{peak} = \frac{.0029\ m}{T}$$

$$\Rightarrow T = \frac{.0029\ m}{\lambda_{peak}}$$

$$\Rightarrow T = \frac{.0029\ m}{480 \times 10^{-10}}$$

$$\Rightarrow T = 60,400 \text{ degrees Kelvin.}$$

d.) With the temperature, we can determine the energy flux for the star's surface. In this case, that will be

$$F = \sigma T^4$$
$$= \left(5.67 x 10^{-8} W / m^2\right)\left(60,400\ K\right)^4$$
$$= 7.5 x 10^{11}\ joules / m^2 / second.$$

e.) If we hadn't used a space based telescope to gather our data, our deductions would *not* have been possible. How so? The earth's atmosphere screens out most of the electromagnetic frequencies that are produced by astronomical object. In fact, the only frequencies it allows through are those in the *radio frequencies range* and those in the *optical range* (there is also a little bit of infrared and a little bit of ultraviolet, but not much). To determine a peak black body frequency for the star we were looking at, given that its peak was well into the ultraviolet range, we would have had to have used data from a space based telescope like the Hubble.

i.) As a minor side point, this is why the ozone layer is so important. That is the part of the atmosphere that absorbs out ultraviolet radiation.

G.) Some Observations About A Star's Color:

1.) From a star's color or, more specifically, from the peak frequency coming in from the star, we can use what we know about black body radiation to determine the star's *surface temperature.*

2.) The problem is that our atmosphere doesn't let all frequencies through, so land based telescopes are at a disadvantage if the peak frequency of a star is not in the optical range. Fortunately, rockets provide a way around this problem.

3.) Because the *black body radiation curve* is so well understood, it is possible to measure the intensity of just *two* frequencies of light from the star to determine where along the frequency line that star's black body radiation curve belongs.

a.) A blue filter (called a *B filter*) is used on a telescope to allow only violet to blue light to pass through. That provides one bit of data. Then, a yellow to green filter (called a *V filter*) is used.

b.) Although determining the intensity in these two ranges would allow astronomers to fit the black body curve appropriately, there is no need to do even that. We know so much about the curve, all that is needed are the intensity values measured using the *B* and *V* filters and the known relationship that exist between those two frequencies. With that information, we can pin point a star's surface temperature without doing anything else.

4.) Bottom line: The color of a star really does allow us to deduce how hot the star is.

H.) A Word About *Apparent* and *Absolute* Magnitude Scales:

1.) Although it isn't particularly earth-shaking in its *inherently interesting* rating, anyone who plays around with astronomy is bound to run into what is called the *apparent* and *absolute magnitude scale*. To be complete, I am saying a little something about this now.

2.) The *apparent magnitude scale* is a way to categorize stars by their *apparent brightness*. Two thousand years ago, the brightest stars were tagged as *first magnitude* stars, the next brightest stars tagged as *second magnitude* stars, and the least brightest stars (i.e., the faintest as viewed in a clear mountain or desert sky) as *sixth magnitude* stars.

Note: This means the lower the rating, the brighter the star.

3.) Later, after the scale was set, it was observed that the span of five magnitudes (i.e., from the *first* to the *sixth* magnitude) corresponded to a brightness variation, as measured by energy flux, that ranged over a factor of approximately 100.

Note: The problem with using our eyes as our measuring device for light intensity is that the eye has a *logarithmic* sensitivity response. That is, the firing rate of neurons in the eye is proportional to the *log* of the brightness. What does that mean? The change in the firing rate for an increase of 10^6

times the brightness of a source is 6 times the change of the firing rate for an increase of 10 the brightness of a source. If the eyes didn't work this way, our Cro-Magnon ancestors would not have been able to hunt by both moonlight and sunlight.

This logarithmic nature is also true of hearing, which is why we use the *decibel* (logarithmic) *scale* for measuring sound . . . and why you concert goers will not be *completely* deaf by the age of thirty.

a.) This means that each magnitude was separated by about 2.5 times in brightness.

b.) In other words, just as the difference in brightness between a *third order* star and a *fourth order* star is 2.5 times, the difference in brightness between a *fourth order* and *fifth order* star is also 2.5 times.

c.) Expanding this further, the difference in brightness between a *third order* and *fifth order magnitude* star is $(2.5)^2$ and, in general, the difference in brightness between a star of order *a* and a star of order *b* is $(2.5)^{(b-a)}$.

4.) With the advent of better telescopes, not to mention space-based telescopes, the scale has extended in both directions.

a.) The sun has an apparent magnitude rating of -26.8.

b.) Our closest neighbor, Alpha Centauri, is rated at 0.

c.) The faintest star viewable with the Hubble telescope is rated at 30.

5.) *Absolute magnitude* is an attempt to normalize (i.e., make uniform) apparent brightness values. *Absolute magnitude* is defined as the *apparent magnitude* of a star if the star was 10 parsecs away from the earth. (At 3.3 light years per parsec, this is a distance of 33 light years.)

a.) Our sun, which looks bright because it's close but which isn't inherently a very big or bright star, has an *absolute magnitude* of 4.8.

b.) The significance of the sun's *absolute brightness* number is that if we were only 10 parsecs away, the sun would seem like a very dim star (remember, 6 is associated with a star that is just barely visible with the naked eye).

6.) Because it is scaled to *apparent brightness* at 10 parsecs, *absolute magnitude* can be used as a measure of a star's luminosity. That is, the smaller the *absolute magnitude*, the more energy the star is putting out.

I.) A Word About Spectral Classifications:

1.) Originally, spectral classifications ordered stars by their hydrogen spectral lines (i.e., very prominent, not so prominent, etc.). Stars with the most prominent hydrogen spectral line were characterized as *A* type stars, stars with a little less prominent hydrogen spectral line were characterized as *B* type stars, etc.

2.) With time, astronomers realized it was more useful to tag stars by their surface temperature. Instead of giving up the old system, though, they simply rearranged the letters they already had to fit the new scheme.

class	temperature
O	30,000^o Kelvin
B	20,000^o Kelvin
A	10,000^o Kelvin
F	7,000^o Kelvin
G	6,000^o Kelvin
K	4,000^o Kelvin
M	3,000^o Kelvin
L	2,000^o Kelvin
T	1,000^o Kelvin

3.) Until recently, the spectral classifications included the first seven classes shown in the table. The pneumonic used to remember them was, "**O**h, **B**e **A F**ine **G**irl (or **G**uy), **K**iss **M**e."

4.) Because we now have identified stars--brown dwarfs--whose mass is not large enough to ignite hydrogen fusion but whose mass *is* large enough to fuse deuterium, the last two classes were added.

a.) One possible mnemonic for the new group is, "**O**h, **B**e **A F**ine **G**irl, **K**iss **M**e **L**iv **T**yler."

b.) Another possible mnemonic is, "**O**fficially, **B**ill **A**lways **F**elt **G**uilty **K**issing **M**onica **L**ewinsky **T**enderly."

5.) Knowing a star's surface temperature tells you a lot about what to expect from its spectrum. Whether you would expect strong, moderate, or weak spectral lines in ionized hydrogen, ionized helium, ionized heavy elements, hydrogen, helium, heavy elements and metals--it is all predictable (and observable) dependent upon the star's surface temperature and, hence, its spectral class. Conversely, what shows up in a star's spectrum tells you about its temperature.

6.) The spectral classification is further scaled from 0 to 9 with the lower numbers corresponding to hotter stars.

a.) Our sun at 5800 degrees Kelvin is rated at *G2*.

b.) Betelgeuse, the red supergiant found in the upper left shoulder of the constellation Orion, is rated at *M2*.

J.) Determine the Mass of a Star:

1.) As has been the case with most of the observations we have made, if we need the mass of a distant star, the trick is to find a star with similar spectral characteristics that is close and whose mass can be determined, then assume the two will be the same.

2.) So how do we measure the mass of a nearby star? About the only way we have of doing this is if the star is a part of a binary system. This is needed because the orbital period and either the orbital velocities or orbital distances of stars in a binary system are related to the mass of the individual stars by what is called Kepler's Law.

Although we will derive them later in the year when we study Newton's Laws, and although this is something you should *not* memorize, there are two forms of Kepler's Law that are pertinent here (this assumes you are looking at a *large* star and a *small* star in the same system). The first form is $GM = \left(\frac{2\pi}{T}\right)^2 a^3$, where G is a constant, M is the mass involved in the star system being examined (effectively the mass of the large star), and a is the orbital distance between the stars, and T is the period of the motion. The second form is $GM = \left(\frac{T}{2\pi}\right)v^3$, where v is the orbital velocity of the motion.

3.) As for how we can get the information needed to use Kepler's Law:

a.) To get the *orbital period* of the binary system:

i.) Look at how the two spectra from the two stars red and blue Doppler shift as the stars move toward us or away from us in their orbits (this works even if the binaries are so far away that *look* like one star);

ii.) Assuming they are oriented relative to the earth so as to eclipse one another, look at how the luminosity of the pair varies as one star goes behind the other (this works even if the binaries are so far away that they *look* like one star);

iii.) Or by visually observing the orbital components of the star, assuming it is close enough to actually see the two stars separately with a telescope.

b.) If we want our second piece of information to be the *orbital velocity* (i.e., if you are going to use $GM = \left(\frac{T}{2\pi}\right)v^3$), assuming we are looking at the orbiting stars *in the plane of their motion*, we can record the Doppler shift of the light spectra from each star, then use our knowledge of Doppler effect to determine their velocities.

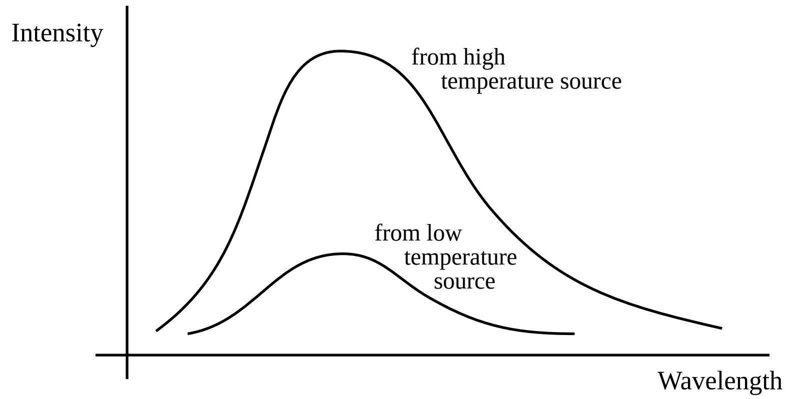
c.) If we want our second piece of information to be the *orbital distances* (i.e., if you are going to use $GM = \left(\frac{2\pi}{T}\right)^2 a^3$), the easiest way to go is to just look at the distance between the two stars visually, assuming they are close enough to be seen.

K.) A Loose End--The Origin of Stellar Spectral Lines:

1.) Back in Chapter 3, it was observed that, "Stars give off white light, but for reasons that will be expanded upon in Chapter 5, stars "absorb out" certain frequencies of that light. That means that when star light is passed through a prism or diffraction grating, frequency gaps called *spectral lines* are observed." With your understanding of blackbody radiation, we can now make sense of that claim.

2.) The first thing of importance to note is that blackbody radiation is temperature dependent. That is, the hotter the source, the more intense the radiation.

3.) So let's assume you have two sources of radiation, one at low temperature and one at high temperature. Relative to one another, the black body radiation curves for the two sources will look something like that shown in the sketch.



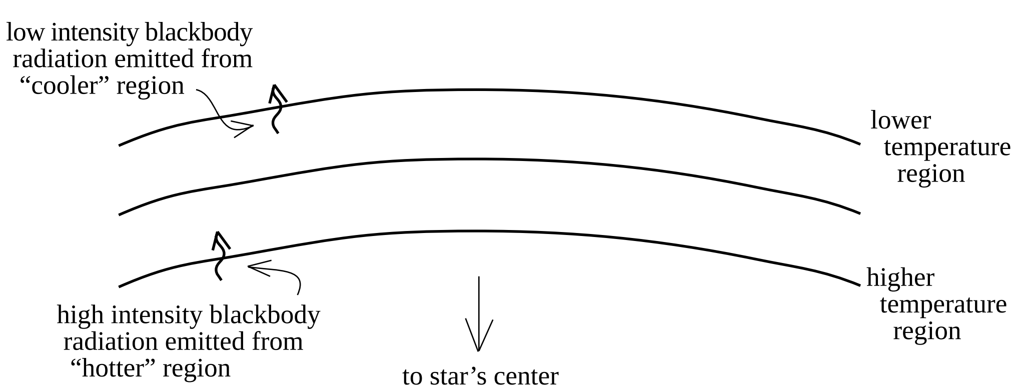
Note: Temperature variation also shifts the peak wavelength, which the sketch doesn't show, but we aren't interested in that characteristic right now, anyway.

4.) Consider now the thermal cross section of a star.

a.) Deep inside the star, the temperatures will be relatively high.

b.) Close to the star's surface, the temperatures will be relatively low.

c.) As the intensity of blackbody radiation is temperature dependent, the blackbody radiation being emitted from hotter depths of the star will have a higher intensity than the blackbody radiation being emitted from the cooler shallows (see sketch).



5.) If that was all that was going on, all the radiation coming from the depths of a star would escape and the radiation curve for the star would correspond to blackbody radiation at relatively high temperature. There is more, though, which alters that expectation.

6.) Think back to how light is emitted.

a.) When an atom is excited, it boosts one of its valence electrons into a higher energy orbital. Once there, after a very short time, the electron cascades down to lower and lower energy orbitals giving off energy/radiation with each jump.

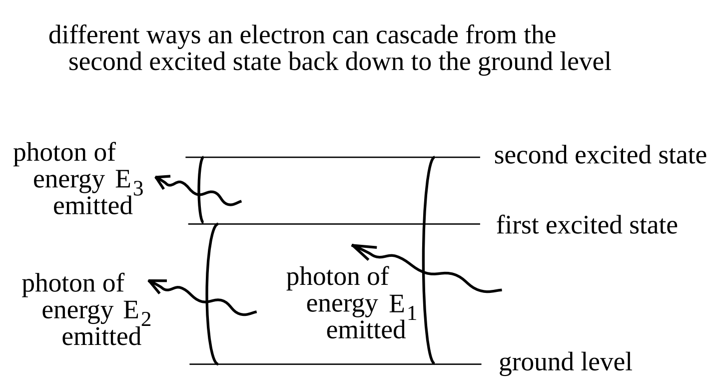
b.) When a gas made up of atoms of the same kind are excited, one electron in each excited atom will follow some cascade path back down to the ground level. That means that as you observe the gas, you will see photons of differing energies being emitted.

c.) So let's say you zero in on one of those atom, and let's assume that that atom is excited so as to boost one of its electrons from the *ground state* to the *second excited state*. As the electron cascades down to its ground level, it can:

i.) Give off energy E_1 (this corresponds to a jump from the *second excited state* directly down to the *ground state*) or;

ii.) Give off energies E_2 and E_3 (this corresponds to a jump from the *second excited state* to the *first excited state*, then a jump from the *first excited state* down to the *ground state*).

iii.) The point is that the atom could emit energies corresponding to three different radiation frequencies (call them ν_1, ν_2, and ν_3) each of which has a wavelength associated with it (call them λ_1, λ_2, and λ_3). The sketch shows this in detail.



d.) Put a little differently, within the atomic structure of that atom are very specific energy jumps that, when an electron takes them, correspond to very specific emitted photon energies and their corresponding radiation frequencies and wavelengths.

7.) What you learned when we talked about emission spectra was that the energies an atom can give off due to its internal energy orbital structure are the very energies that same atom can *absorb* when free photons pass in proximity to the atom.

That was what the idea of an *absorption spectra* was all about--atoms being able to absorb photons of particular energies--energies that corresponded to energy jumps in the atom.

8.) So back to our example atom, if the excited atom can give off energies E_1, E_2, and E_3 at radiation frequencies ν_1, ν_2, and ν_3 and wavelengths λ_1, λ_2, and λ_3, it can also ABSORB photons of energies E_1, E_2, and E_3 at radiation frequencies ν_1, ν_2, and ν_3 and wavelengths λ_1, λ_2, and λ_3.

9.) So back to our star.

a.) Down deep inside the star, very intense blackbody radiation is being given off. Most of that radiation escapes the star. As a consequence, you will SEE that radiation if you look at the star from a distance.

b.) Unfortunately, not *all* of the radiation from the depths of the star will travel out of the star unfettered. There are specific frequencies (wavelengths) of radiation that correspond to photons of specific energy that match up with the energy jumps intrinsic within the atomic structure of the star.

In other words, there are specific wavelengths that get absorbed by the star's atomic structure before they can escape that radiation can escape.

c.) Those absorbed wavelengths are subsequently re-emitted after absorption, then re-absorbed by atoms nearer the surface, then re-emitted, then re-absorbed by atoms still nearer the surface, etc., as they make their way out toward the star's edge.

d.) What is interesting is that by the time that radiation actually exits the star, it finds itself emitted from atoms that exists within the *relatively low temperature environment* of the star's shallows.

As such, the blackbody radiation at that wavelength is LOW INTENSITY.

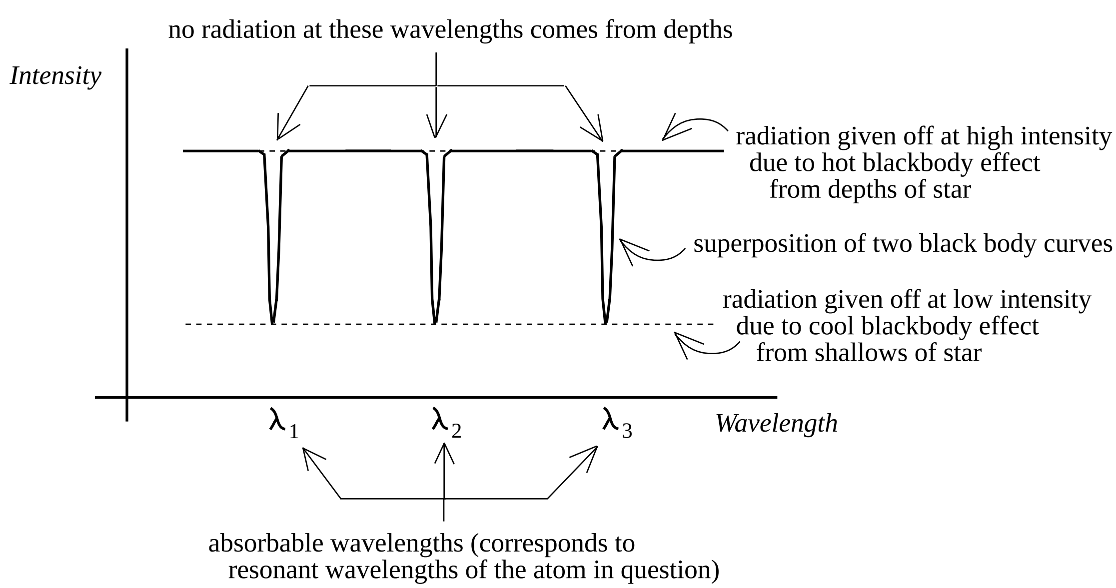
e.) So what kind of light do we see coming out from the star? Two types:

i.) We see a whole lot of light at high intensity that has originated deep within the star. This is the light whose wavelengths doesn't happen to correspond to the resonant wavelengths of the atoms making up the star.

ii.) Superimposed on the deep-origin light is light at low intensity that has originated near the star's surface. This is the light whose wavelength does correspond to one of the resonant wavelengths of the atoms making up the star. It has been absorbed and re-emitted a lot on its way out of the star thereby leaving the star from low temperature atoms. Its intensity, therefore, is low.

f.) If you look at a tiny part of the overall radiation curve (see sketch), you can see how the superposition of these two catagories makes up the light we see.

Looking at a *Very Small Section* of a Star's Black Body Radiation Curve



9.) The bottom line of all of this is that there is a mechanism that produces the spectral lines we see when we look at stars like our sun.

10.) What's more, the spectral lines will differ depending upon the overall temperature of a star's surface.

a.) A star with a very cool surface, relatively speaking (i.e., a star in the 3000^o K range), still has molecular compounds that haven't been torn apart by thermal activity within the star. Stars in this range produce spectral lines that are typical of the energy jumps found in *molecules* like carbon monoxide and titanium oxide.

i.) In hotter stars, all molecular structures are disassembled due to thermal activity. In such stars, molecular spectral lines do not exist.

b.) In stars where the surface temperature is, say, $6{,}000^o$K (our sun is an example of one such star), we see hydrogen lines. Why? Because those temperatures are not high enough to ionize hydrogen atoms, so hydrogen atoms in such stars have electrons available to make energy jumps.

Note: "A" type stars in the 8000^o K to $10{,}000^o$ K range are famous for their hydrogen lines (specifically, the Balmer series that originates from hydrogen's ground state). On the other hand, helium lines are very weak in "A" type stars because their photospheres are not hot enough to excite even the lowest excited state of helium.

c.) In stars where the surface temperature is, say, $30{,}000^o$K, all of the hydrogen atoms have had their electrons completely stripped from them (i.e., they are completely ionized), so we find *no* hydrogen lines of any kind. In such stars, we instead find singly ionized helium lines (these look just like hydrogen lines but at 4 times the energy).

11.) <u>Bottom line</u>: Although this is going to seem a bit anti-climatic, by looking at which spectral lines are present in a star's spectrum, we can determine *the star's temperature.*

12.) And this is an example of one of those situations in which the path to the answer is a whole lot more interesting than the answer itself.

PHYSICS EXAM SUMMARY 2004-2005

There is a lot of stuff covered below, some of which I didn't talk about but did cover in the notes. Also, don't forget the material covered in the Cosmology chapter (Chapter 3) on stellar evolution.

1.) What is the name of the plane upon which the night's stars appear to reside?
2.) What is the celestial plane?
3.) What is the ecliptic plane?
4.) If you put your hand up at arm's length and look at your pinkie, what angle is subtended?
5.) What is the earth's tilt?
6.) What is the period of the earth's wobble about its axis?
7.) What is the current North Star? Is the North Star always the same? If not, why not?
8.) What is the equinox? What are its characteristics and when does it happen?
9.) What is the solstice? What are its characteristics and when does it happen?
10.) When is the earth the closest to the sun?
11.) Why do we have seasons?
12.) Why is it hotter in the summer than in the winter?
13.) On the celestial sphere, what is the coordinate equivalent to *longitude*? Where is its *zero*?
14.) On the celestial sphere, what is the coordinate equivalent to *latitude*? Where is its *zero*?
15.) How is a solar day defined? What are its characteristics?
16.) How is a sidereal day defined? What are its characteristics?
17.) Which is longer, a solar day or a sidereal day?
18.) How many rotations does the earth execute during a solar year?
19.) Why is *leap year* necessary? Who instituted *leap year*?
21.) What is the name of the currently accepted calendar (i.e., who came up with it)?
22.) What information can extract by looking at a star's light?
23.) What is parallax? What is used for?

24.) How is an *astronomic unit* defined? How is a *parsec* defined? How many *light years* are there in a *parsec*?
25.) If Venus is .72 AU's from the sun, and if the earth is 93,000,000 miles from the sun, how far is Venus from the sun?
26.) What does *radar ranging* do? How does it work. When it is useful? When is it not useful?
27.) What is black body radiation? How does the black body radiation curve vary as the temperature goes up? What is the peak frequency of a black body radiation curve dependent upon?
28.) How is *energy flux* defined? How is a star's energy flux related to its surface temperature?
29.) How is *luminosity* defined? How is luminosity related to a stars surface energy flux?
30.) How do we determine a star's energy flux as it exists when it impinges on the earth?
31.) What is the *inverse square law*?
32.) How can knowing a star's luminosity and energy flux (as measured at the earth) allow you to determine the distance to the star?
33.) What do you need to know to determine a star's radius?
34.) What is a standard candle? Give three examples.
35.) What is a Cepheid variable? What are the important characteristic of Cepheid variables? Why is that characteristic important?
36.) What is *apparent brightness*?
37.) What is the relationship between a photon's energy content and its associated frequency?
38.) What is a *watt*? That is, a *watt* is a measure of what?
39.) What does the color of a star tell you?
40.) What is the *apparent magnitude scale*?
41.) What is the *absolute magnitude scale*?
42.) How much brighter is a second order magnitude star and a fifth order magnitude star? Know how you got that number.
43.) What are the spectral classifications? (Hint: One of them is "O")
44.) IGNORE how a star's mass is determined.
45.) How are spectral lines in stars produced? Be complete. That is, how is blackbody radiation affected by the temperature of the source? How does the intensity of blackbody radiation from the interior of a star differ from the blackbody radiation coming from close to the star's surface? Why does all of the more intense blackbody radiation from the interior of a star *not* reach the star's surface?

46.) Why do the spectral lines from a 3000^{o} K star differ from the spectral lines from a 6000^{o} K star? (This has to do with star temperature and atomic ionization--understand what this means!)

47.) What is one kind of atom that produces spectral lines in a 3000^{o} K star but not in a $30,000^{o}$ K star?

48.) What is one kind of atom that produces spectral lines in a $30,000^{o}$ K star?