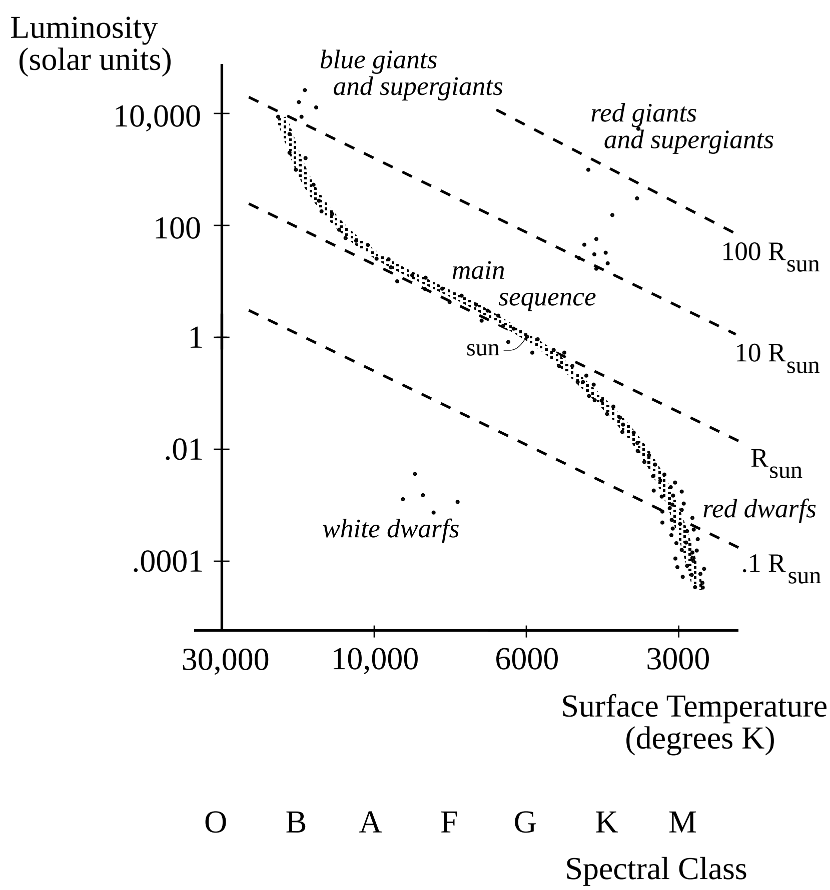
Chapter 6

THE LIFE AND DEATH OF A STAR, and THE H-R DIAGRAM

A.) Hertzsprung-Russell Diagrams:

1.) The *Hertzsprung-Russell diagram* plots *luminosity* versus *temperature*. Aside from its primary use (i.e., if you can determine a star's surface temperature, the H-R diagram will give you its luminosity), it is a useful educational tool in the sense that it highlights in the universe order out of what would otherwise appear to be disorder.

Hertzsprung-Russell diagram



2.) The basics of the *H-R diagram* and things you need to understand about the system follow.

a.) Temperature on the H-R diagram ranges from 30,000 degrees Kelvin to 3000 degrees Kelvin (those temperatures are plotted backward--odd, but that's the way some astronomers are--a little bit of physicist humor). It plots from *O type* to *M type* stars (we talked about *spectral classification* earlier).

b.) The luminosity scale is expressed in terms of *luminosity of the sun*. That is, on a H-R diagram, L = 1 is found in the middle of the plot and denotes the sun's position on the diagram.

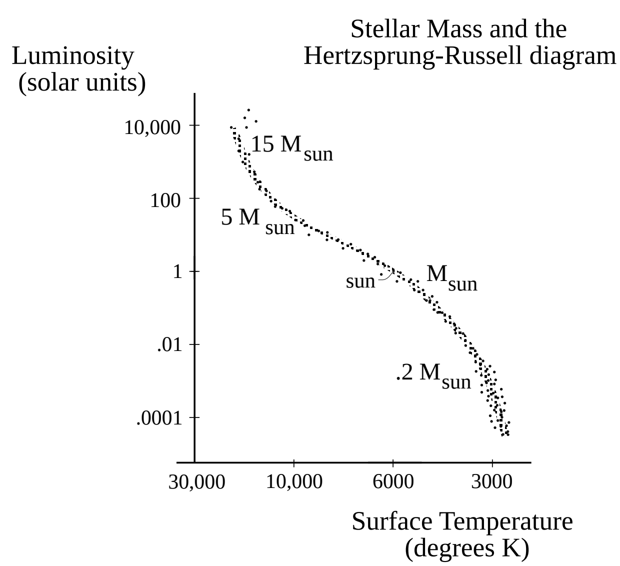
c.) Luminosity on the H-R diagram ranges from 10^{-4} to 10^{4}. Again, *1* denotes the luminosity of the sun.

d.) Stars plotted in a H-R diagram are not uniformly spread out over the plot. Not surprisingly, hot stars tend to have high luminosity whereas cooler stars tend to have lower luminosity.

3.) In general, the plot was originally created by plotting information for stars we already knew something about.

4.) The plot is useful for determining the luminosity of stars we do not know about given only their temperature (remember, this can be obtained by looking at their color and *black body radiation curve*).

5.) The luminosity L of a star is numerically equal to the star's surface area $4\pi R^2$ times its energy density σT^4, where R is the star's radius and T its surface temperature. If you know a star's luminosity and temperature, you can determine its radius. That information correlates on the H-R diagram (in fact, it is included in terms of solar radii on the H-R diagram shown on the first page of this chapter).



6.) From observation, it is evident that the more massive a star, the farther up the *main sequence* it resides on the H-R diagram. A rough approximation of this is shown in the sketch.

7.) Useful trivia:

a.) Although we haven't yet discussed why a star might be a *red dwarf*, it turns out that 80% of stars in the universe *are* red dwarfs (look on your H-R diagram now to see where they reside). Found in the bottom right-hand corner of the H-R diagram, the size of these stars is in the vicinity of *one-tenth the radius of the sun* (i.e., .1 R_{sun}).

i.) Almost all of the stars near the earth are red dwarfs, yet this is not something you would probably conclude for yourself because you wouldn't *see* any when you look into the night sky with your naked eye. What you would see would be a lot of bright, blue giants even though there are very few of them in the universe. Why?

ii.) You don't see red dwarfs because they are not luminous enough *to* see, and because the selection device you have chosen to use (i.e., your eyes) more or less precludes seeing them. If, instead, you used a space ship to move through a given volume, counting stars, almost all of the stars you would find using *that* device would be red dwarfs.

b.) Of the twenty brightest stars in the sky, only 6 are within 10 parsecs of us. The rest are visible due to their large size and luminosity.

c.) Only *one ten-thousandth* of the stars in the universe are type *O* and type *B* "blue giants." These are located in the upper left hand corner of the H-R diagram. Their radii are around *ten times that of the sun* (i.e., 10 R_s).

d.) During the normal lifetime of a star (i.e., after it has emerged from being a protostar--an infant--and before it begins its death throes), it will reside somewhere on what is called *the main sequence* of the H-R diagram. This comprises approximately 90% of the stars in our vicinity.

e.) From observation, it is evident that the mass of a star fits onto the H-R diagram. Specifically, the more massive the star, the farther up the *main sequence* it resides (i.e., the brighter and hotter it is). A very rough approximation of this is shown in the sketch.

i.) This shouldn't be too much of a surprise. A 2005 Ford GT has a top speed of 205 mph and a 20 gallon gas tank. At 205 mph, its range is 70 miles and its "lifetime" is about 20 minutes. A Toyota Pries has a top speed of 100 mph and an 11 gallon gas tank. At 50 mph, its range is 600 miles and its "lifetime" is about 12 hours.

Fast and furious translates into a short lifetime.

ii.) How does this translate for stars? A 30 solar mass star is very big and very bright. It has a lifetime of around *six million years* (i.e., 6,000,000 years) before it supernovas and turns into a neutron star. A .3 solar mass star is small and dull. It has a lifetime of around *four hundred billion years* (i.e., 400,000,000,000 years).

8.) There are two things to do in trying to understand the working of the universe in conjunction with the H-R diagram.

a.) As a star lives its life, it will change its coordinate on the H-R diagram. That is, its size and luminosity will change over time depending upon what is happening inside the star. The first thing we need to look at is how stars evolve and, as a consequence, why they move around on the H-R diagram.

b.) The second thing we need to look at is how groups of stars that all come from the same interstellar stuff and all start their pre-star gravitational collapse at about the same time proceed with time. That is, for stars whose only difference is their mass, when and where do they place themselves on the H-R diagram.

c.) We will look at both of these questions in the next several sections.

B.) Stars Smaller Than 8 Solar Masses:

1.) We talked about the life of a typical star a few chapters back. In that discussion, it was noted that during the main part of a small star's life , the star will primarily convert hydrogen into helium at its core.

2.) At some point (10 billions years for a star like the sun), the star will begin to run out of fusible hydrogen in its primarily helium core.

3.) As hydrogen fusion begins to diminish due to lack of fuel, the core cools, the outward pressure normally provided by heat from the fusion process diminishes, gravity takes over, and the core begins to collapse. This happens about 10 million years after the star has entered the *main sequence*.

4.) As the core collapses, gravitational potential energy is released and the core begins to heat in a non-nuclear way. As this happens, hydrogen begins to fuse quite radically in a shell of previously unburned hydrogen just outside the core. (This is sometimes called the *hydrogen shell burning stage*.)

a.) What this means is that as the nuclear reaction at the core diminishes, *the star gets brighter*.

b.) What it also means is that as the shell outside the core burns via fusion, it releases nuclear energy that pushes the outer shell--the envelope of the star made up of hydrogen that is not fusing--outward. That is, *the star gets larger*.

c.) As the envelope expands outward, it cools, which it to say that its energy flux decreases even though its luminosity goes up.

Note: This may seem counterintuitive, but it makes sense if you think about it. If the energy being given off per unit area per unit time (i.e., the energy flux) goes down, but the area gets a lot bigger, it is possible that the total amount of energy being given off (i.e., the smaller energy flux times the larger area) might go up. That, in fact, is what happens.

5.) The process outlined above takes around 100 million years to happen. As it does, the star climbs what is called the *red giant branch* on the H-R diagram.

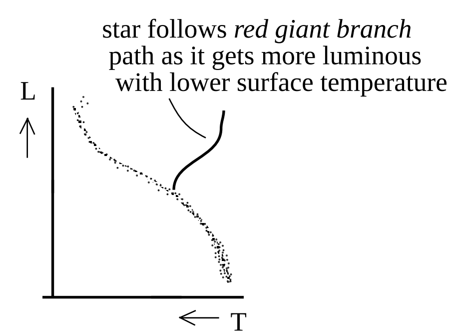
a.) Toward the end of this process, the star is around 100 times the radius of the sun.

b.) It has luminosity that is around 100 times that of the sun.

c.) Its core size is around the size of the earth (i.e., this is around one ten-thousandth the size of the star itself).

d.) And the tiny core has compacted to enormous density and now contains approximately 25% of the star's mass.

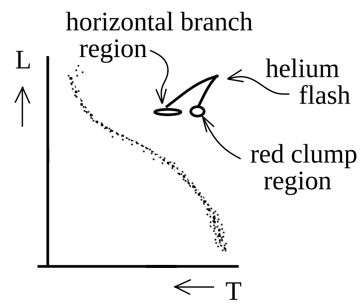
e.) A depiction of where the star has gone on the H-R diagram is shown to the right.



6.) When the shell outside the core makes the core hot enough--approximately 100,000,000 degrees Kelvin, helium begins to fuse to make carbon in the core in a runaway nuclear reaction called a *helium flash*. This stops the star's ascent up the *red giant branch* of the H-R diagram.

7.) Within a few hours, the helium flash ceases as the star's core expands enough to allow the gravitational force inward and the core radiation pressure outward to come into equilibrium.

a.) By this time, the star--a red giant--has moved into a stable situation in which helium is fusing in the core to make carbon, and hydrogen is still fusing to make helium in a shell just outside the core.



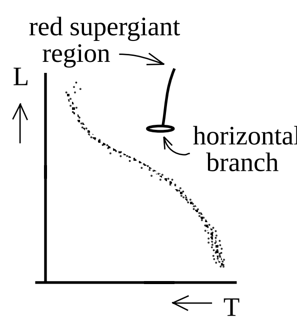
b.) As the star has moved to this situation, it's coordinate on the H-R diagram settles down to either the *red clump* region or the *horizontal branch* region.

i.) What is the difference? Later generation stars that have elements other than hydrogen and helium in them go to the *red clump* region. First generation stars that are nearly pure in hydrogen and helium go to the *horizontal branch* region.

ii.) Where *red clumps* and *horizontal branch* stars belong on the H-R diagram is shown to the right.

7.) Within 20 million years, the core, having become primarily carbon, begins to run out of helium fuel.

a.) As was the case in the hydrogen cycle, once the helium fusion process begins to diminish, the star's core begins to contract and the core temperature begins to rise from non-nuclear heating.



b.) Due to the core temperature increase, helium begins to fuse in a shell just outside the core. In a shell just outside that, hydrogen continues to fuse. In other words, there are two shells of material outside the core, one of hydrogen and one of helium, both producing energy via fusion.

8.) With the hydrogen and helium fusion happening in shells in the vicinity of the edge of the core, the outside envelope of the star once again begins to expand. What is different is that because the temperatures are so much higher this trip, the expansion is even greater than the first time around and we end up with what is called a *red supergiant*. (It's also called a *asymptotic giant branch star*.)

9.) In the *red supergiant* stage, the non-fusioning core continues to contract. If the core temperature reaches 600 million degrees Kelvin, carbon fusion ignites and the whole cycle repeats itself just as it did when the helium core began to fuse.

a.) As a star the mass of the sun has a peak core temperature of around 300 million degrees Kelvin, stars like the sun do not have enough mass to move to this carbon fusing state. They end their lives as carbon white dwarfs (the real *diamonds in the sky* . . . and thank you, Sterl Phinney).

b.) Red supergiants can be as large as 400 to 500 times the size of the sun.

i.) Put a little differently, in 10^{10} years from now our sun will swell up and engulf first Mercury, then Venus, Earth, Mars, and maybe even Jupiter.

10.) Due to the high core temperatures, atoms making up the material of the core have long since been ionized and the core has an enormous population of free electrons. Assuming the star's size is such that no carbon fusion ignites, gravity continues to collapse the core until those free electrons are no longer able to be squeezed together any closer.

a.) Put a little differently, because electrons are not willing to degenerate into a situation in which there is more than one electron per quantum energy state, they produce a kind of *degeneracy pressure* that stops the shrinkage.

b.) Put more differently still, it is as though the electrons have been squeezed to the point where they act like rigid balls that have been jammed together as close as they can get.

c.) What you end up with is a very hot core--not hot enough for carbon fusion, but hot nevertheless--whose density is around 10^{10} kg/m^3.

i.) If you wanted to duplicate this density on earth, you would have to take a *car* and compress it down to the size of a marble.

11.) Before the degeneracy pressure stops the shrinkage, the star's core compression pushes the temperature in the shells outside the core higher and higher motivating the hydrogen and helium in those shells to fusion-burn faster and faster. The outer shell continues to expand outward, cooling in the process. Finally, the outer *envelope* ejects into space at a speed of up to 20,000 m/s.

a.) This shell of cooling matter is called a *planetary nebulae* (its a misnomer, but they were called that because they look like fuzzy planets through a telescope).

b.) A *planetary nebulae* is an outward moving shell of glowing gas that surrounds what had become a naked star core.

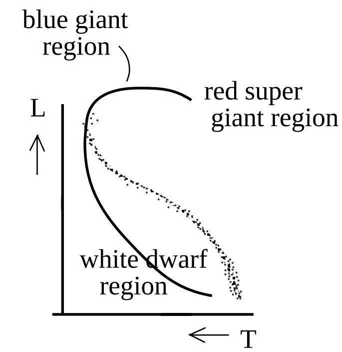
c.) If you'd like a fun time on the Internet, the following Web sites have pictures of planetary nebulae:

http://www.noao.edu/jacoby/pn_gallery.html (big collection)
http://hubblesite.org/newscenter/newsdesk/archive/releases/2004/11/ (neat)
http://hubblesite.org/newscenter/newsdesk/archive/releases/2003/11/
http://hubblesite.org/newscenter/newsdesk/archive/releases/2000/28/
http://hubblesite.org/newscenter/newsdesk/archive/releases/2000/12/
http://hubblesite.org/newscenter/newsdesk/archive/releases/1999/01/
http://hubblesite.org/newscenter/newsdesk/archive/releases/1998/39/
http://hubblesite.org/newscenter/newsdesk/archive/releases/1998/15/
http://hubblesite.org/newscenter/newsdesk/archive/releases/1997/38/
http://hubblesite.org/newscenter/newsdesk/archive/releases/2004/10/ (this is an image of red supergiant's wind--it is the predecessor of planetary nebula).

12.) With the core now exposed, it glows white and is called a *white dwarf*. At this stage, the radiation output is not the consequence of fusion but rather from residual, stored heat.

a.) Interesting note: White dwarfs have the same temperature as larger main sequence stars, but they are much smaller in size (their radius is a hundredth that of the sun). Because they are so small, they are much less luminous.

13.) As the white dwarf continues to cool, it fades away. This is how stars the size of the sun die.



14.) The death phase H-R diagram path for stars of this size is shown in the sketch.

15.) What is fascinating about all of this, if you think about it, is that you can find in the night sky bright blue stars, and huge red stars, and little bitty white stars, and they are all the same kind of star--they're just existing at different times of life. A red supergiant, in other words, is just a relatively young star that will, some day, be a white dwarf.

C.) Novas:

1.) As an interesting aside, if the white dwarf is close to a binary partner (i.e., if it is one of two stars that orbit one another), it is possible for the very dense and, hence, gravitationally massive white dwarf to gravitationally suck hydrogen and helium away from the other star.

2.) If this happens, the stolen material will swirl around the white dwarf forming what is called an *accretion disk* around the dwarf. Due to friction, this orbiting material gradually spirals in and falls onto the white dwarf.

3.) As more and more gas accumulates on the white dwarf, temperatures at the bottom of the pile rise. When that temperature reaches the 10 million degrees Kelvin required to initiate hydrogen fusion, the gas ignites nuclearly and a huge amount of energy is released in a very short time--maybe a few days.

4.) During the brightening, the stars intensity can increase as much as 60,000 times only to slowly go back to normal over a few months. Also during brightening, the top of the pile of accreted matter is ejected into interstellar space.

5.) This process can be repeated dozens or even hundreds of times during a white dwarf's life time.

6.) On the Web:

a.) For a look at a nova that was bright one week, then dark two weeks later, go to http://www.arksky.org/NOVACYGNI.jpg.

b.) For a look at the light curve of a spectacular nova, go to http://www.aavso.org/vstar/vsots/v1500.shtml.

D.) Stars Greater Than 8 Solar Masses, and the *Core Collapse* Supernova:

1.) The events in the lives of stars whose mass is greater than eight solar masses is similar to that of stars that are less than eight solar masses. They will fusion-burn a succession of elements, hydrogen, then helium, etc., at their core. There are differences, though.

a.) One of the main difference between lightweight stars and massive stars is that the more massive stars burn much faster and, as a consequence, are considerably shorter lived.

b.) Also, during the various periods during which the core is not hot enough to begin fusion on the element that happens to populate the core at the time (i.e., during the period when the core is compressing producing non-nuclear heating), there will be more and more shells outside the core fusing elements of lower atomic number than that found at the core.

i.) That is, toward the end of really massive star's life, it will have shells (going from outside in) of fusing hydrogen, then helium, then carbon, oxygen, neon, magnesium, and silicon.

ii.) Each shell produces fuel for the next shell.

d.) What's more, the amount of time taken for each core fusion process to complete itself will become less and less as core temperatures get higher and higher. As expressed in Chaisson and McMillan's *Astronomy*, "A star 20 times more massive than the sun burns hydrogen (in its core) for 10 million years, helium for one million years, carbon for 1000 years, oxygen for one year, and silicon for a week. Its iron core grows in less than a day."

e.) And finally, if the star is really massive, it will be able to fuse elements all the way up to iron.

2.) In very massive stars, the end comes when the core becomes iron.

3.) How so? Fusion to make all elements up to iron *give off energy* in the process. Fusion to make all elements bigger than iron *take in energy*. Once a star gets to an iron core, energy-producing fusion ceases.

4.) Because core fusion begins to diminish as the core becomes more completely iron, at some point gravity takes over and the core begins to collapse. The collapse raises the core temperature through non-nuclear heating.

5.) When the core temperature hits 10 billion degrees Kelvin, photons energies are high enough to break the core atoms into smaller atoms, then those smaller atoms into their elementary components (i.e., protons and neutrons).

6.) With the proton/neutron/electron/photon core at super high density, electrons are forced into protons to make neutrons, giving off neutrinos in the process.

a.) The density required to do this is on the order of 10^{17} kg/m^3.

b.) If you wanted to duplicate this density on earth, you would take a *10^8 ton* of material (that's 1000 Nimitz class aircraft carriers, or a fairly sizable hill like Mt. Wilson)) and compress it down to the size of a marble.

7.) The collapse continues unfettered until neutrons in the core begin to bump up against one another. (This is similar to what the electrons did in stopping the collapse of white dwarfs.)

8.) As the collapse slows, it *overshoots its equilibrium situation*, then rebounds back outward (this is like a superball dropping onto the floor). Only about a second passes from the time the collapse starts to the rebound.

9.) So how does the star blow?

a.) Until recently, physicists thought that the compression-induced expansion (i.e., the bounce) produced a shock wave that literally blew the outer portion of the star outward creating what is called a *core collapse supernova*. But just as a superball won't recoil higher than its drop height (assuming it isn't thrown), computer simulations show that the shock wave doesn't have enough energy to overcome the damping that happens as it passes through the stuff of the envelope, and the envelope never does blow off.

b.) Physicists then assumed that the energy needed to blow the envelope came from the neutrinos that were released when electrons and protons combined to make neutrons. These neutrinos would have to pass through the envelope as they exited the star. If 1% of the energy carried by the neutrinos was coupled with the outer mass of the star, it would blow the envelope. Unfortunately, computer models so far show that there isn't quite this much coupling between neutrinos and matter, and the computer simulations fizzle after almost going bang.

c.) What this all comes down to is that we have some fairly well educated guess as to what is happening, but we haven't yet nailed the process. The one thing we *are* sure of is that nature has no problem executing this operation. Supernovas happen, and that's all there is to it.

10.) During a supernova of this kind (i.e., a core implosion supernova), the star gives off billions of times more energy than our sun and as much as a 100 time the energy the star has produced *in its entire lifetime* . . . all released in about 10 seconds.

a.) In 1054, a supernova was observed by Native Americans (we've found wall paintings highlighting the occurrence) and the Chinese that was so bright, it could be seen *during the day* for over two weeks.

Interestingly, it must have been foggy over Europe during the occurrence because no one there reported the sighting.

11.) During a supernova, so much energy is available that elements of atomic number higher than iron--elements that *take energy in* when they are made through fusion--can be made. That is, a large proportion of the atoms in our universe whose atomic number is higher than *iron* were made when stars died via supernovae.

a.) You might wonder where the rest come from. In fact, when a large star is in its *helium shell burning stage* on the *asymptotic giant branch*, it is possible for free neutrons to be forced into the core's iron nuclei (these nuclei were created in some long-ago supernova which "polluted" the hydrogen and helium from which this star formed) due to high core pressure. As more and more neutrons accumulate in a given iron atom, its nucleus gets larger and heavier. At some point, the nucleus radioactively decays with some neutrons turning into protons and electrons. That is, the decay effectively *adds* protons to the nucleus. As *proton number* determines the kind of element you are looking at, the net effect is that the atom's atomic number increases and we end up with an element that is "bigger" than iron.

12.) The material that is blown outward from a supernova is called a *supernova remnant*. These can be seen in the X ray range, the radio frequency range, and the optical range (the optical range is observable due to heat generated by radioactive decay of the elements within the remnant).

13.) The Web has an amazing amount of information and pictures of supernovas and supernova remnants.

a.) Latest supernovae found by astronomers (images & list) at http://www.rochesterastronomy.org/supernova.html

b.) The Crab nebula (i.e., Messier 1 . . . or the 1st in Messier's list of objects "to be avoided when hunting for comets") is a remnant of Supernova 1054 AD. It can be seen at http://nssdc.gsfc.nasa.gov/image/astro/hst_crab_nebula.jpg

c.) A poster that has nice photos and example of extragalactic supernova before/after can be found at http://www.tifr.res.in/~akr/golden.html

d.) The remnant of the supernova 1987A (this was in a nearby galaxy, which also was one of brightest naked eye stars at its peak) shows the supernova before and at peak of supernova. This is at http://www.aavso.org/vstar/vsots/0301.shtml

e.) Light from a supernova and the now expanding gas illuminating the wind that flowed out of star during presupernova state can be seen at http://hubblesite.org/newscenter/newsdesk/archive/releases/1994/22/ AND http://hubblesite.org/newscenter/newsdesk/archive/releases/1998/08/

f.) Remnant of supernova of 1680 (Flamsteed)--Cassiopeia A. This is an X-ray image of hot gas in remnant (inner section shows the hot shocked gas of the stellar envelope, outer: hot shocked gas of interstellar medium) at

http://chandra.harvard.edu/photo/2004/casa/

g.) Cassiopeia A in various wavelengths (radio-Xray) at http://coolcosmos.ipac.caltech.edu/cosmic_classroom/multiwavelength_astronomy/multiwavelength_museum/casA.html

h.) The remnant of Supernova of 1572AD (Tycho) at

http://chandra.harvard.edu/photo/2002/0005/index.html

i.) Other supernova remnants in X-ray are at:
http://chandra.harvard.edu/photo/2004/n49b/
http://chandra.harvard.edu/photo/2003/snr0103/index.html
http://chandra.harvard.edu/photo/2002/0050/index.html

j.) Other supernova remnants in radio (you are looking at synchrotron radiation from cosmic ray electrons orbiting the magnetic fields while being accelerated in the supernova shock wave) are at http://www.physics.usyd.edu.au/astrop/wg96cat/gallery.b.html

k.) The remnant of a Type Ia supernova explosion (white dwarf detonation, not collapse of massive star core) at http://chandra.harvard.edu/photo/2003/deml71/index.html

E.) Star Clusters and the H-R Diagram:

1.) How does a cluster of stars whose only difference is their mass evolve with respect to the H-R diagram? That is what this section will address.

2.) To begin with, it should be noted that star clusters are nice because all of the stars in the cluster came from the same interstellar stuff, and they all begin to form at approximately the same time. That means the only real difference between one star and the next in a cluster is its mass.

3.) The most massive stars in our cluster will form first, going from the protostar stage (i.e., collapsing their interstellar material down to fusion-burning temperature) fairly quickly. They will then burn very bright and very fast. These are the *O type* stars (i.e., blue supergiants).

4.) After 10 million years, most of the hot, bright, blue supergiants will have run their course and will have died via supernova. At that point, the interstellar material making up intermediately sized stars will have finally collapsed to the point of igniting fusion, and those star will come onto the *main sequence*.

5.) At 100 million years, most of the smaller *M type* stars will have reached the *main sequence*. Stars in the upper *B range*--blue giants--will be the hottest stars in the system at this time.

6.) Going on the observation that hotter, larger stars burn faster than smaller, cooler stars, stars leave the *main sequence* for the red giant phase from the top of the *main sequence* down. That means that the upper part of the *main sequence* de-populates first in a relatively orderly way. As it does, the red giant and red supergiant area begins to populate.

7.) After a billion years, *A type* stars are leaving the *main sequence* and the lowest part of the *main sequence* is populated as much as it is going to be. By this time, white dwarfs have also begun to appear.

8.) At 10 billion years, stars like our sun are leaving the *main sequence*.

9.) Thus, by observing the H-R diagrams of star clusters and galaxies, we can determine when those clusters and galaxies formed. The oldest clusters are about 12 billion years old. When (before 1998) cosmologists claimed the universe was less than 10 billion years old, this was a problem. But now, with the 1998 discovery of dark energy, cosmologists claim it is 13.5 billion years old, vindicating our knowledge of stars.

F.) The White Dwarf Supernova:

1.) In fact, it turns out that there are two general types of supernova. There are ones that have hydrogen show up in their spectra and ones that don't.

2.) *Type II* supernova have already been explained. They are the *core collapse supernova* discussed above, and they have hydrogen in their spectrum. *Type I* supernovas have no hydrogen in their spectrum.

3.) *Type I b* and *Type Ic* are also core collapse supernovas, just like *Type II* supernovas, but they do *not* have hydrogen in their spectrum.

a.) Why do they have no hydrogen in their spectrum?

b.) These are massive stars that have lost their hydrogen to a nearby companion star before exploding (remember, white dwarfs in a binary system will steal hydrogen from the envelope of their larger companion if near enough).

4.) *Type Ia* supernovas are associated with white dwarfs. Because white dwarfs are essentially star cores that don't have outer shells, they are hydrogen free, hence no hydrogen in their spectrum.

5.) So how do tiny white dwarfs create *Type Ia* supernovas?

a.) We have already talked about how the accretion disk around a white dwarf *in a binary star system* can ignite in hydrogen fusion creating the energy burst associated with a novas.

b.) What's important here is that all of the mass does not necessarily blow when the star novas. The consequence is that as time proceeds, the mass of the white dwarf increases.

c.) If a white dwarf becomes more massive than 1.4 solar masses, the electrons that are holding the core up from collapsing further can no longer handle the pressure and the core collapses.

d.) If this happens, the internal temperature of the white dwarf will increase rapidly to the point where carbon can actually be fused. When this happens, this carbon fusion process happens throughout the entire core almost simultaneously and the entire star explodes.

e.) This *carbon detonation supernova* puts out energy comparable to a *core collapse supernova.* (For the purists out there, the detonation might really be a deflagration, but who's counting?)

5.) In fact, some scientists maintain that two white dwarfs colliding can merge to produce the extra mass needed to initiate this kind of supernova. In any case, because there are no envelopes involved, there will be no hydrogen in the explosion.

6.) In short, although the end results are similar--huge amounts of energy released over a very short period of time (i.e., a few days)--the mechanism that drive the *core collapse* and *white dwarf* supernovas are completely different.

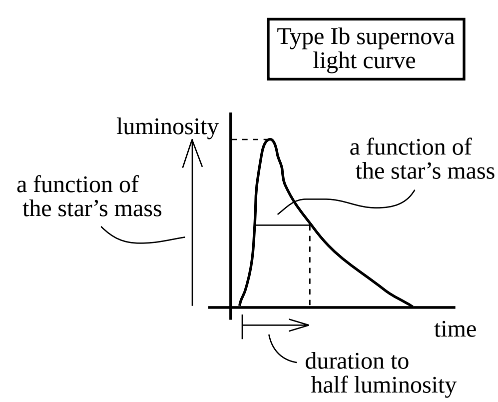
7.) One of the final points of interest about supernovae is that the duration of their light curves are related to the *luminosity* of the explosion.

a.) How so? The total energy given off in the supernova is determined by the mass of the star.

b.) The time for the energy to escape is at first determined by the mass of stuff the radiation has to scatter through on its way out through the star.

c.) What this means is that both the maximum energy output (i.e., luminosity) and the initial time of energy escape as measured by a decrease in luminosity are related to the same thing--the star's mass.

d.) In fact, the bottom line is that the amount of time it takes the supernova to drop to half brightness is related to the maximum luminosity of the explosion (see sketch).



The duration to half brightness is related to the supernova's luminosity.

Note: The energy that is given up after that half-way time point is due to radioactive decay. If, for instance, there is one solar mass worth of ^{56}Ni (i.e., nichol) made in the fusion of the supernova, it will decay into ^{56}Co and ^{56}Fe. ^{56}Co is an unstable isotope of cobalt that has a half-life of 6 days before it radioactively decays into something else, giving off energy in the process. ^{56}Fe is an unstable isotope of iron that has a half-life of 77 days before it radioactively decays into something else, giving off energy in the process. It is this energy that illuminates the supernova after the initial luminosity explosion.

e.) Remembering that if we know the luminosity of a celestial object along with its *apparent brightness*, we can determine the distance to the celestial object, this is HUGE. It means that if we observe *Type Ia* (the brightest) and *Type II* supernova in another galaxy (and, in fact, all observed supernovas since modern astrophysics have *been* in other galaxies--the last in our galaxy was in 1572), all we have to do to determine its luminosity and, hence, its distance, is measure how long it takes for the supernova's luminosity to halve, and we can determine the distance to that galaxy.

G.) The Core of a Supernova–Neutrons Stars and Black Holes:

1.) A star's mass is what determines whether the end result of its core at death is a white dwarf, a neutron star, or a black hole.

2.) If the core mass is less than 1.4 solar masses:

a.) The electron degeneracy pressure will be able to counteract gravity and stop core implosion.

b.) The core will die as a white dwarf.

c.) Our sun is in that camp.

3.) If the core mass is less than 1.8 solar masses but greater than 1.4 solar masses (this would correspond to stars that had been between 15 to 20 solar masses overall):

a.) The core electrons fighting quantum intrusion will become so energetic that they "go relativistic" (i.e., their energy will exceed 1 MeV).

b.) When that happens, electrons that meet protons will combine to form neutrons giving off a neutrino in the process.

c.) What stops the implosion is *neutron*s fighting quantum intrusion (i.e., neutrons shoved up against one another).

d.) What you end up with is a ball of neutrons about 10 kilometers across that has a mass density of 10^{17} to 10^{18} kg/m^3.

e.) If you wanted to duplicate this density on earth, you would have to take *10^8 to 10^9 tons* of stuff and compress it down to the size of a marble.

f.) As a minor side point, just as an ice skater's *angular velocity* increases as she pulls her arms in during a spin, the sudden diminishing of radius (i.e., from the size of, say, the sun, to 10 km across) means the once slowly rotating core ends up rotating at incredibly high angular speed.

i.) We have observed neutron stars that rotate from *one tenth* to 600 revolutions *per second*. (We haven't yet talked about *angular momentum* and the *conservation of angular momentum*, but when we do this will make more sense.)

ii.) Because neutron stars put out energy directionally in the radio frequency range, we first observed these as very fast, periodic blasts of radio waves coming in from space. Not knowing the origin of the emission, they were attributed to objects that were and still are called *pulsars*.

iii.) There is a pulsar at the center of the Crab Nebula (this is the nebula associated with the supernova in 1054 AD) that flashes on and off 33 times per second. To see this on the Web, go to http://nssdc.gsfc.nasa.gov/image/astro/hst_crab_nebula.jpg

iv.) The sound from a pulsar radio emission (audio frequency!) can also be heard at http://www.jb.man.ac.uk/~pulsar/Education/Sounds/sounds.html

v.) There is another very cool site that has a lot of pulsars, including sound and a movie. It is at http://www.jb.man.ac.uk/research/pulsar/Education/Sounds/

g.) In a nutshell, then, a pulsar is a rapidly rotating neutron star whose electromagnetic radiation in the radio frequency range is modulated at its rotation period.

4.) If the core mass is greater than 1.6 solar masses:

a.) The core will be so massive that *nothing* can stop the implosion.

b.) You end up with a black hole. We will talk more about these when we discuss Relativity.

H.) You Are Star Stuff:

1.) Most of the hydrogen and helium in the universe was created shortly after the Big Bang. Almost everything else came later . . . but from where?

2.) Stable lithium was produced during the Big Bang.

3.) All of the beryllium and boron in the universe is the consequence of high energy protons accelerated in supernova remnants hitting carbon atoms in the interstellar gas, splitting off part of the carbon leaving beryllium and boron.

4.) All of the elements from *carbon* up through *iron* were produced through fusion at the core of normal, healthy stars during the course of their lifetime. That process stopped at iron, though, because fusing elements larger than iron requires energy *input*. In fact, *core collapse supernovas* happen because iron rich cores can go no farther in energy production through fusion.

5.) Where did the elements of higher atomic number than iron come from?

a.) Some were produced during supernovas when incredible amounts of energy are available to force smaller elements to fuse into elements larger than iron. In other words, heavy elements were produced during supernovas whereupon they were spewed out into the universe as nebula.

b.) Some were produced in the core of stars when neutrons that had been slowly injected into iron nuclei radioactively decayed increasing the atomic number of the iron to something other than iron.

6.) A supernova not only produces elements heavier than iron, its shock wave additionally produce the density imbalance required to start the gravitational collapse of interstellar stuff resulting in the formation of *new* stars and star clusters.

a.) This is the reason it takes a *third generation* star to get planets like our own rich in heavy elements. It takes that much time to accumulate enough stuff to populate a solar system with more than hydrogen and helium.

7.) The point here is that you and I and everything around us is *star stuff*. The gold in your jewelry, the copper in our electrical wires, the lead that is hopefully not in our water, the uranium some fight over in our attempt to keep the power industry from using fissionable materials in atomic power plants to produce electricity, the oxygen you breathe, the carbon in you and in the things you eat, they all were created sometime during the life and/or death of a star.

Without stellar evolution, all that would exist within the universe would be a whole lot of hydrogen, some helium, and a bit of lithium.

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. I hope you took advantage of your reading day last Wednesday.

1.) What does the "H-R" on a H-R diagram stand for?
2.) What are the axes of a H-R diagram?
3.) If given a sketch of a H-R diagram, be able to name the types of stars that reside at various places on the sketch.
4.) 90% of the stars in our vicinity are of what spectral class?
5.) Blue giants are how many times the size of our sun?
6.) Red supergiants are how many times the size of our sun?
7.) Which burns faster, an "O" type star or an "M" type star?
8.) In main sequence stars, what is happening during "the hydrogen shell burning stage")
9.) What is the only difference between a main sequence star and a star in the *horizontal branch region*?
10.) What stops a star's ascent up the *red giant branch*?
11.) How long do *helium flashes* last?
12.) How is *boron* made in the universe? (No, it's not due to fusion)
13.) In a star in which carbon can not ignite into fusion, what happens? That is, how does this star "die."
14.) What is a *planetary nebulae*? (This is related to question 57) What is left after a star goes through the process of producing a planetary nebulae?
15.) As a star gets older and older and leaves the red super giant region, where does it go on its way to death?
16.) What is a *nova*? How are they produced? What must be true for one to happen?
17.) What is a *core collapse* supernova? A star must be at least how big for one to occur?
18.) What elements are typically produced in a star large enough to supernova before the star supernovas?
19.) A star 20 million times more massive than the sun will core burn hydrogen for 10 million years. For how long will it core burn iron?

20.) During a core collapse supernova, how much energy is given off, and how fast does it happen?
21.) When did the Chinese see a supernova, and for how long was it bright?
22.) What is produced during a supernova?
23.) The material that is blown outward during a supernova is called what?
24.) IGNORE the section on *Star Clusters and the H-R Diagram*.
25.) What is a *white dwarf* supernova, and how is it differ from a *core collapse* supernova? Also, what "type" is a *white dwarf supernova*?
26.) What is the difference between a *Type I* and *Type II* supernova?
27.) How are *Type Ib* and *Ic* supernovas alike to the *Type II* supernova?
28.) What is the duration of the light curve of a supernova related to?
29.) How will our sun die?
30.) What is a neutron star?
31.) What is a black hole?
32.) What is a pulsar?
33.) What are you?