Key concepts for material since Nov 10, 2011 ASTR 100 exam

Note: for the final *everything* in the entire class is fair game. Thus anything in lecture, discussion, homeworks, or our textbook could be used. The following are key concepts since the second exam to help you focus your studies.

- High-mass stars evolve faster than low-mass stars at all stages. This is because, to hold themselves up against gravity, they need to produce energy faster by fusion. For stars that begin their lives with more than 8 times the mass of the Sun, their main sequence (as usual) is where they fuse hydrogen to helium; then later they fuse helium to carbon, carbon to oxygen, and so on up to iron. The energy per nucleon (proton or neutron) bottoms out at iron, so (a) they get less and less energy at each fusion stage and have to burn hotter and hotter because of increased electrical repulsion as the charges of the nuclei get greater, and (b) iron doesn't release energy when it fuses, so it's a dead end and the iron builds up as a dead lump. When the mass of the iron core gets to the Chandrasekhar mass (about 1.4 times the mass of the Sun), electron degeneracy can no longer hold up the iron core and it collapses, releasing an enormous amount of energy that blows apart the outer parts of the star in a massive star supernova and leaves a neutron star or black hole in the middle.
- The fusion in the cores of massive stars produce the elements between helium and iron, and the supernova itself produces the heavier elements, which are dispersed during the blast. Thus most of the elements in the periodic table are due to supernovae; in a very real sense, we are made of star stuff.
- A star can end its life as one of three types of object: low-mass stars (beginning their lives with less than about 8 times the mass of the Sun) become white dwarfs. These are objects with roughly the mass of the Sun but roughly the size of the Earth. They generate no energy of their own but are held up by electron degeneracy pressure. Higher-mass stars (starting with between 8 and about 20-25 times the mass of the Sun) become neutron stars. Neutron stars are sublimely beautiful objects :) with masses that might be between 1.2 to 2 (possibly 3?) times the mass of our Sun that could fit into a city (radii 8-15 km; not well known). They also generate no energy of their own but are held up by neutron degeneracy pressure. The highest-mass stars (starting with 20-25 times the mass of the Sun) become black holes. Black holes could theoretically have any mass. We have evidence for black holes between 3 times the mass of our Sun and 10 billion timees the mass of our Sun. They are gravity's ultimate victory; they have no surface, and all their mass is concentrated at a point.
- Gas can spiral onto a white dwarf, neutron star, or black hole from a companion. Conservation of angular momentum tends to flatten out the matter, so these are *accretion*

disks. Just as with planetary orbits, the inner parts of accretion disks orbit faster than the outer parts, so there is friction in the disks. This heats them up; the hottest parts of neutron star and black hole disks can reach millions of degrees and thus emits mainly X-rays. The hydrogen and helium from a companion can pile up on a white dwarf or neutron star (but not a black hole, since those have no surfaces) and can thus lead to explosive fusion. On a white dwarf this is known as a *nova* and on a neutron star this is known as an *X-ray burst*. If enough matter falls onto a white dwarf to push it over the Chandrasekhar limit, the collapse triggers catastrophic fusion of the carbon in the white dwarf and this completely destroys the white dwarf in a white dwarf supernova. These are very important in cosmology because their intrinsic luminosity is known. Neutron stars were first detected as *pulsars*; basically, beams of radio waves come out of a neutron star's magnetic poles, and if we happen to be in the right direction we see pulses of radio waves as the star rotates. Think of a rotating lighthouse where we see the beam as it rotates.

- Black holes, gravity's ultimate victory, do not have surfaces. Instead, there is a region called the *event horizon* that is close enough to their center that the escape speed $v_{\rm esc} = \sqrt{2GM/R}$ equals the speed of light c; this is called the *Schwarzshild* radius after its discoverer, and $R_S = 2GM/c^2$. This is 9 km for a three solar mass black hole, and is proportional to the mass of the hole (thus unlike white dwarfs and neutron stars, which get smaller as their mass gets bigger because they are held up by degeneracy pressure, more massive black holes are bigger). When we normally think of escape speed we think of an object that gets higher but slows down and is eventually brought back; for a black hole, however, once inside the event horizon nothing can make *any* progress outward; it is like being on a walkway moving faster than you can, so you are dragged in inevitably. If you were a freely falling point mass you would not notice anything strange falling into a black hole. But you're not, and the gravitational force on your feet (if you fall feet-first) is greater than on your head, so there is a tidal force along your body. This would get stronger as you got closer to the black hole, eventually ripping you apart. The difference across your body at the horizon is less for more massive black holes; you could enter the event horizon of a billion solar mass black hole without feeling anything, but you'd eventually get ripped apart as you got closer to the *singularity* (the point where all the mass is concentrated).
- Although we focus on the weird effects that apply very near black holes (time dilation, gravitational light deflection), far enough from a black hole its gravity acts just the same as the gravity from anything else of that mass. For example, if the Sun were magically turned into a black hole of one solar mass, Earth's orbit would be unchanged. Black holes need to be detected via their influence on other things. We can, for example, see stars orbiting the black hole at the center of our galaxy. Supermassive black holes are also the power sources of "active" (very bright) galaxies; again, the energy does not

come from the hole itself, but from the gas in the accretion disk around it.

- Our galaxy, the Milky Way, contains perhaps two hundred billion stars and is 50-500 thousand light years across depending on where you draw the line. The inner few thousand light years are the *bulge*; the bulge contains $\sim$20% of the stars, which are old, low-mass, and have a small proportion of elements heavier than helium. These stars move in random orbits (like a basketball). The next 30-50 thousand light years are the *disk*; the stars basically move in the same plane and in the same direction (think of the shape of a Frisbee). This contains $\sim$ 80% of the stars, which are both old and young and have more heavy elements. The outer part, reaching to hundreds of thousands of light years,is the *halo*. It has $<$ 1% of the stars, few heavy elements, and the stars move in all directions (basketball). We can measure the mass of our galaxy using the speeds of stars and their distance from the center of the galaxy, or from the light of the stars; oddly, these do not give the same answer, suggesting that there is *dark matter* in our galaxy. In our galaxy, gas is recycled to a degree: starting in atomic clouds it cools to molecular clouds, which condense to form stars, which live their lives and give back much of the mass to the interstellar medium (via winds or supernovae), which then forms stars. But mass is progressively locked up in stellar remnants (white dwarfs, neutron stars, and black holes), so with time the gas available for star formation is reduced in its supply.

- In addition to spiral galaxies (such as our Milky Way), there are *elliptical* and *irregular* galaxies. Ellipticals have little gas and thus little star formation, so their stars are old, red, and low-mass. They are "all bulge" in that their stellar orbits are every which way. Ellipticals can be any size; really big ones are found at the centers of galaxy clusters. Irregulars have lots of gas and thus lots of active star formation. They are irregularly shaped and small. Galaxies like to congregate. Many are found in *groups* of tens of galaxies within a few million light years. Our Local Group has about 60 known galaxies in that volume. In contrast, *cluster* contain thousands of galaxies within the same space (a few million light years). The typical distance between galaxies is just 10-100 times their size, so galaxies collide. In contrast, the distance between stars is tens to hundreds of millions of times their size, so the stars don't collide even if their galaxies do. Galaxy collisions take hundreds of millions of years (comparable to orbit times around a galaxy), because they are so huge. Although the stars in galaxies don't collide when the galaxies do, their interstellar media do collide. This leads to lots of shocks of the type that cause gas to condense and form stars, so collisions of spiral galaxies lead to very rapid star formation, hence exhaustion of their gas, hence produce ellipticals (little gas, little ongoing star formation). Some galaxies are "active" (much more luminous than normal); these are powered by accretion disks spiraling into supermassive black holes.

- The "Great Debate" between Curtis and Shapley was about the nature of the "spiral nebulae". To resolve their nature it was necessary to determine the distances to the spiral nebulae. There are many ways you could imagine measuring the distance to things, including direct measurement, parallax, "standard ruler" (if you look at an object of known size, its angular size tells you its distance), and "standard candle" (if you look at an object of known luminosity, its brightness tells you its distance) methods. Remember that the luminosity L of an object is related to its brightness b and distance d from you by $L = 4\pi d^2 b$, so if you know L and measure b then the distance is $d = \sqrt{L/(4\pi b)}$. Edwin Hubble used one type of standard candle, Cepheid variables, to show that spiral nebulae are indeed galaxies comparable to the Milky Way. Cepheids are bright stars whose luminosity varies in a periodic way: the longer they take to vary, the more luminous they are, so by knowing their period you know their luminosity.

- Hubble also discovered that the recession speed of a galaxy (as determined from the redshift of its spectral lines) is directly proportional to its distance. Thus, Hubble's law is $V = H_0 d$, where $H_0 = 71$ km s^{-1} Mpc^{-1} is the Hubble constant (recall that 1 Mpc is a million parsecs, or about 3.26 million light years). You might think that this means we are in the center of an explosion, but in fact *all* parts of the universe are expanding away from each other; we are not in the center. Indeed, a useful principle is the cosmological principle: there is nothing special about where we are, so over large scales the universe is the same everywhere (it is *homogeneous*) and looks the same in all directions (it is *isotropic*). What it does mean, if you run the film backward, is that the universe originated a finite time ago (13.7 billion years) in a Big Bang.

- There are three key indicators that the universe started in a hot Big Bang, meaning that it was once much denser and hotter. First, universal expansion: going back in time the universe had to be hotter and denser. Second, this would imply that it was hot enough to radiate at one point, and we do see the remnant background glow we expect (this is called the Cosmic Microwave Background, or CMB). Third, when the universe was *much* smaller than it is now, just a few minutes after the Big Bang, conditions would have been right to convert hydrogen to helium, although it was not possible to get to heavier elements. This is called *Big Bang nucleosynthesis*, and it explains the amount of helium in the universe (there is far too much to explain as the result of fusion in stars).

- The fate of the universe and its geometry (basically, how light rays travel) depend on the amount of mass it has. Too much, and after expanding for a finite time it stops and recollapses. Too little, and it expands forever. Density is destiny: it determines the age, geometry, and ultimate fate of the universe.

- We can only see directly about 4% of the mass and energy of the universe. Indirect evidence exists for *dark matter*, which would be matter that does not emit light but does have mass and gravity, and which would explain the rotation of galaxies. We have not, however, seen this in laboratories, and it would have to be made of particles we have never detected. Even more mysterious is *dark energy*. Since 1998 it has been determined using observations of distant white dwarf supernovae that the universe's expansion is getting *faster*. This means that there has to be some kind of repulsive force pushing it apart, and this is called dark energy for lack of a better term. This is exactly the effect that Einstein's cosmological constant would have, but we do not yet have a satisfactory understanding of what it exists or the strength of the force.

- Earth is the only place in the universe that we know to have life. Once life forms, its subsequent development is well explained by evolution, which is the unifying concept of biology and which has had its fundamental concepts confirmed by innumerable observations and experiments. The *fact* of evolution is that forms of life change over time, via descent with modification. The *theory* of the mechanism is developing and being enriched with time, just as all theories are (including gravity). The basic idea is that reproduction leads to variation (via mutation, or sexual combination, or other mechanisms). Some of that variation will be advantageous, in terms of leaving more viable offspring. Those variations then spread through the population. Note that variation is not *purposeful*; it is the equivalent of blindly grasping in innumerable different directions at once, through the whole population.

- Life on Earth started nearly four billion years ago, and was single-celled life until maybe 800 million years ago. Life is everywhere on Earth that there is an energy source and liquid water; we don't know how general this is. If it is true elsewhere, then given the enormous number of stars and planets in the universe it seems inevitable that life must exist elsewhere, even if it is only microbial. Intelligent life is a different story; difficult to tell. It is very unlikely that intelligent life has visited Earth from elsewhere; the distances are vast, and no verifiable evidence exists (note that personal testimonials are notoriously unreliable, and hard evidence is lacking). Thus alien life is likely, but visits from aliens are very unlikely!