Astronomy 102: Stars and Galaxies
Spring 2003

Final Exam Review Topics

The final exam will cover material from the whole course (including the galaxies and cosmology material from after Exam 3). The topics you should be familiar with, and some of the most important details, are listed below.

You will be allowed to bring one, one-sided $8.5'' \times 11''$ page of notes with you to the final. (That's inches, not arcseconds.) These notes must be your own, in your own handwriting; you cannot share a note page with friends.

You do not need to memorize any equations; any equations or constants you need will be on the front of the test.

No books will be allowed on the final, but you will need a calculator.

Motions in the Sky

- Celestial Coordinates
  - Right Ascension : East-West
  - Declination : North-South
  - At a given latitude on Earth, when you look to the west, which direction *on the sky* is due west? North? Etc.
  - Locations: Celestial poles, equator, zenith, meridian, circumpolar stars
  - Be able to add and subtract angles to figure out how high something on the meridian will be.
- Earth/Sun/Moon geometry
  - What causes the seasons?
  - What causes the phases of the Moon?
  - Month = roughly the period of the Moon's orbit.
  - The same side of the Moon always faces Earth.
- Angular Diameters: measuring angles on the sky
  - The small angle formula: $d\,A = D$ where D is the physical diameter of an object, A is the angular diameter you measure for the object (in radians), and d is the distance to the object.
- Measuring distances to stars with parallax: $d = \frac{1}{p}$ where d is the distance in parsecs and p is the parallax in arcseconds.

Gravity

- $F = \frac{GMm}{r^2}$: F=gravitational force between two objects, M=mass of one object, m=mass of the other object, r=distance between the objects. Closer = *stronger* force.
- As two objects get closer, gravitational potential energy is released as another form of energy. E.g., when you drop something towards the Earth, as it gets closer to the Earth it moves faster. Gravitational energy is being converted to energy of motion in this case.
- Gravity is what holds one object in orbit around another.
- Kepler's laws: $P^2 = A^3$ in our solar system; P=period of orbit in years, A=semi-major axis of orbit in AU.

Light

- Waves
  - Frequency, Amplitude, Wavelength
  - $f = \frac{c}{\lambda}$; c is the speed of the wave (the speed of light for light!)
- The Electromagnetic Spectrum
  - It's all light; what we can see is "visible light"
  - Longer wavelength = lower frequency = redder
  - Radio, infrared = longer wavelength than red light
  - Ultraviolet, X-rays, Gamma rays = shorter wavelength than blue light
- Photons
  - Energy of one photon: $E = hf$ where f is the frequency of the light, and h is Planck's Constant.
- Luminosity and Flux
  - Luminosity = how much energy per second an object puts out
  - Flux = how bright an object looks (i.e. how much energy a detector (telescope, eye, etc.) of a given size would collect per second)
  - $F = \frac{L}{4\pi d^2}$ where d is the distance from an object of luminosity L to the observer, and F is the flux seen by that observer. How bright an object looks depends not only on its intrinsic luminosity, but also how far away it is.
  - Using the equation in the previous point to measure distances using the *method of standard candles.*

- Redshift / Blueshift
  - The Doppler effect: $\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$; $\Delta\lambda = \lambda_{\text{obs}} - \lambda$, where λ is the original (emitted) wavelength of the light and λ_{obs} is the wavelength you observe. v is the velocity of the object emitting the light relative to you, and c is the speed of light. A *redshift* happens when $v > 0$, i.e. the object is moving *away* from you. A *blueshift* happens when $v < 0$, i.e. the object is moving *toward* you. (This equation works for $v \ll c$, i.e. for speeds a lot less than the speed of light.)
  - Cosmological Redshift: the redshift tells you *how much the universe has expanded* since the light was emitted. $\lambda_{\text{obs}}/\lambda$ = (Size now)/(Size when emitted).

Light and Matter

- Thermal Radiation
  - A *high density* object (e.g. the Sun) will emit thermally.
  - Thermal bodies emit at a wide range of wavelengths.
  - Anything above absolute 0 temperature emits (even you)
  - Hotter = bluer (a greater fraction of its emission is at shorter wavelengths)
  - For two objects *of the same size*, a hotter object is more luminous.
  - $L = (4\pi R^2)(\sigma T^4)$: L, here, is the luminosity of a spherical body of radius R and temperature T. (Note! R is the radius of the emitting body, *not* the distance to the body!) σ is the Steffan-Boltzman constant, a well-known value that may be looked up.
- Atomic/Molecular Emission and Absorption
  - Atoms and Molecules have specific energy levels
  - *Emission Lines* and *Absorption Lines*: Transitions between energy levels can lead to emission or absorption at a specific wavelength (i.e. color) for gas where the constituents behave like individual atoms or molecules. Seeing emission or absorption at specific wavelengths allows us to determine what types of atoms and molecules we are looking at.
  - A *low density* gas will typically show individual atomic lines. A *high density* gas where the particles can interact frequency will typically show thermal emission (above) rather than emission at a specific frequency.
  - Ionization: Some (or even all) electrons are stripped from atoms. (Hydrogen only has one to strip.) Can happen when you have very hot gas (fast moving particles run into each other and have enough energy to ionize each other), or (more often) "photoionization" by ultraviolet light.

Stars

- Flux & Luminosity & Radius (above) and Luminosity & Flux & Distance (above)
- The H-R diagram. (Understand what is being plotted.)
  - Bluer stars are hotter (See also above)
  - The "Main Sequence" are stars like the Sun, generating energy by fusion of Hydrogen to Helium at their core. Stars spend about 90% of their life on the main sequence.
  - More massive main sequence stars (compared to the Sun) are larger, hotter, more luminous, and shorter lived than the Sun.
  - Less massive main sequence stars (compared to the Sun) are smaller, redder, less luminous, and longer lived than the Sun.
  - When stars use up their Hydrogen fuel at their core, they start doing other things (Hydrogen shell fusion, Helium fusion), and "leave the main sequence", becoming Giants or Supergiants.
  - The *main sequence turn-off* for a population of stars all the same age tells you how old those stars are. (Higher mass stars/bluer stars higher on the main sequence will leave the main sequence first, because they are shorter lived.)
- Star formation and the Interstellar Medium (ISM)
  - Stars form from gravitational collapse of (relatively) dense, cool gas clouds.
  - Stars form in clusters, many at the same time and same place.
  - The hottest stars ionize the nearby ISM
  - The hottest stars are short-lived, so regions forming stars are bluer in color (since that's the only place young stars can be fount).
  - Stars and supernovae eventually fuse heavy elements; planetary nebulae and (especially) supernovae return these heavy elements to the ISM.
  - The cycle of heavy element enrichment.
- Composition: mostly Hydrogen, some Helium, just a little bit of heavy elements... but all stars we've seen have *some* heavy elements. The heavy element abundance reflects the heavy element abundance of the cloud the star formed from.
- Stellar structure
  - Core: fusion
  - Envelope: non fusing material
  - Photosphere (or surface): what we see directly
  - Outward pressure from the energy generated by fusion balances the gravitational pull inward from the mass of the star

- Stellar evolution
  - High mass stars ($M > 8M_\odot$): fuse elements all the way up to Iron at their core. The iron core collapses down to a *neutron star*, and the gravitational energy released explodes as a *Type II Supernova*
  - Low mass stars (like the Sun): fuse up to Carbon (or maybe a bit heavier, Oxygen or Neon) at their core. Throw off their outer layers as a *planetary nebula*, leaving behind a *white dwarf.*
- Stellar explosions
  - *Nova*: a white dwarf in a binary system pulls matter from a companion. That matter builds up until it reaches enough pressure that the matter explodes, leaving the white dwarf behind.
  - *Type Ia Supernova* (or a *Thermonuclear Supernova*): a white dwarf in a binary system pulls matter from a companion. If the white dwarf can build up to $1.4\,M_\odot$, runaway fusion of the carbon in the white dwarf will blow the white dwarf away.
  - *Type II Supernova*: See above.
- Compact stars
  - White Dwarf: made of Carbon or Carbon and Oxygen; held up by electron degeneracy (electrons are packed together as close as they can get). $M < 1.4\,M\odot$ (usually about half the mass of the Sun), similar in radius to the Earth.
  - Neutron Star: the density of an atomic nucleus, basically pure neutrons packed together as close as they can get (neutron degenerate). $M < 3\,M_\odot$. Typically about the mass of the Sun but only 10 km in radius.
  - Black Hole: When an object is too dense or too massive to bee a neutron star, it forms an *event horizon* of radius $R = 2\,G\,M/c^2$ (M=mass of black hole, G=gravitational constant, c=speed of light). Nothing can escape from inside this event horizon to outside it. Left behind from the core collapse supernovae of the very most massive stars.

Extrasolar Planets

- None have been imaged directly, but about 100 are known.
- Most are found by the gravitational effect of the planet on the star. As the planet orbits the star, the star wobbles, sometimes moving toward us, sometimes away. These wobbles can be observed with the Doppler Effect (above).
- Many of the first planets found were "hot Jupiters", planets around the mass of Jupiter but even closer to their star than the Earth is to the Sun.
- Some Jupiter-mass planets have been found at distances from their stars comparable to Jupiter's distance from the Sun, so planetary systems like our own may exist.

The Milky Way Galaxy

- Components
  - Bulge: spheroid in the middle with a $2.6 \times 10^6 \, M_\odot$ black hole at the center.
  - Disk: flattened, differentially rotating disk, where all the cool gas is, most of the stars are, and all the star formation is. *Open clusters* are clusters of stars formed relative recently (at most in the last few billion years); each cluster of stars formed all at once.
  - Halo: Spheroid of stars and globular clusters, with very *low* heavy element abundances, all very old. No cool gas, no stars forming now.
- Dark Matter
  - Evidence: flat rotation curve of the galaxy is *too fast* for stars further from the center of the galaxy than we'd expect from the mass of all the stars and gas we can see. There must be more mass.
  - In a "dark halo" which extends further than the stellar disk.
  - MACHOs discovered through *gravitational lensing* are "massive compact halo objects" – free floating planets or dark stars (brown dwarfs, cooled off white dwarves, or black holes). They are there, but can't be more than $\sim 20\%$ of the dark matter.
  - Most of the dark matter is exotic particles which haven't yet been discovered, possibly WIMPs ("weakly interacting massive particles").
- Chemical evolution: see "Stars/Star formation and the Interstellar Medium" above.

Galaxies

- Giant galaxies: Spirals and Ellipticals
  - Both have formed stars over a range of ages
  - Spirals are forming stars *now* in their disks: thus they are bluer, have more cool gas, have gas ionized by hot young stars.
  - Elliptical galaxies mostly haven't formed stars in the last 1-2 billion years.
- The Local Group
  - Our galaxy (the Milky Way), the Andromeda Galaxy, and the Triangulum galaxy are large spirals.
  - Most of the rest are dwarf galaxies and/or satellites of the Milky Way or the Andromeda Galaxy
- Galaxies are found in *Groups* and *Clusters* (the latter being "richer", i.e. having more galaxies)

- Clusters themselves are grouped into *superclusters*
- Spiral Structure
  - Most star formation happens in spiral arms: spiral arms are *bluer and brighter* than the space between the arms because of the hot massive stars that go along with star formation, but the contrast in the *number* of stars in arms and between arms isn't that great.
  - Grand design spiral arms are *density waves*: interstellar traffic jams.
  - Because of differential rotation, spiral arms aren't *material arms*; in that case they would wind up. They rotate at a *different* rate than the stars do, so stars pass in and out of spiral arms as they go around the galaxy. The spiral arms are just where the traffic jam is right now.

Cosmology

- The universe is expanding. (Hang on to your hat!)
- Uniform expansion
  - Every point is the center
  - The Hubble Law : $v = H_0\, d$ where d is the distance to a galaxy, v is the speed it's moving away from us, and H_0 is the *Hubble Constant*. This applies in the local universe, i.e. with relatively nearby galaxies.
- The expansion rate changes with time; the universe appears to be *accelerating* (the expansion is getting faster and faster).
- The gravitational attraction of mass would tend to slow down the expansion, so if there were just mass in the universe you'd expect the expansion to be decelerating.
- The universe is make up of three quarters *dark energy*, an unknown exotic *something* which is driving the acceleration. (The other one quarter is matter, but most of *that* is dark matter!)
- The Big Bang
  - The Cosmic Microwave Background: the "afterglow of creation", the left over glow from the hot, dense expanding universe. (Currently 3 degrees above absolute zero, showing a perfect thermal spectrum.)
  - Big Bang Nucleosynthesis: stars with Hydrogen. About 25% of the mass of the universe is Helium, and there's a smidge of Deuterium, Lithium, and Beryllium, and basically *nothing else*. Any heavy elements we see today were made inside stars!
  - The Big Bang happened 13.7 billion years ago. (Compare to 5 billion years, the age of the Sun, or 3.5×10^{-8} billion years, the age of your professor.)