AY 5: Introductory Astronomy–The Formation and Evolution of the Universe

Kathy Cooksey

August 16, 2008

Draft 1: August 16, 2008

1 Teaching Philosophy

1. Lecture design:
   (a) Since Galaxy Inquiry should teach nature of images, can frame future lectures as story about images.
2. During lectures, discussions, etc:
   (a) Count to 10 s after asking for student volunteers.
   (b) During discussions, move around so that by body language I can draw people in or exclude them.
   (c) Demonstrations are good so long as you have a plan for them and drive the point home.
3. Tetris analogy: I do not want to build solid layers at a time to get to the big picture. I want to fit pieces together as best as possible. It would even be fun to build my Tetris construction and label the pieces as the astronomy bits.
4. I want the students to *improve* in their math ability and in their ability to learn.
   (a) Learn to understand the "word problems."
   (b) Look for the (given) equations which use what is given and produce the answer.
   (c) Learn how to read information from articles.

(d) I want students to see as many connections between things as possible.

5. Tell students that I'm always asking for lots of feedback so I can adjust my teaching; "you are the customer."

2 Course Description

- "The universe explained. Fundamental concepts of modern cosmology (Big Bang, dark matter, curved space, black holes, star and galaxy formation), the basic physics underlying them, and their scientific development. Intended for non-science majors. Courses 3, 4, and 5 are independent and may be taken separately." (Astro. Dept. undergraduate course description)
- AY5 satisfies the introduction to natural science (IN) and mathematics (Q) general education requirements at UCSC.
- AY5 is an intensive course that demands students learn the qualitative description of the Universe–past, present, and future–in addition to learning details about select phenomena: properties of light, nuclear fusion, galaxies, etc.
- The students were challenged to apply their (increasing) understanding of physics to problems in order to figure out what equations and constants to use in what order, instead of simply being given the ordered equations and numbers.
- In addition to manipulating equations (*i.e.*, algebra), the students had to use plots and figures to answer questions, either by reading information from the plots/figures or by creating their own figures.

3 Student Feedback

1. On M July 7th (3rd week), gave “reading quiz,” which I had been loosely calling the quizzes, though I had said they would be about new stuff as well as old. One student (who missed part of last lecture) complained.

2. Student reset day (F July 11th):

   (a) Left the room for 10 minutes and let the students come up with what they wanted.

   (b) There was also to be a math quiz that day.

   (c) So they first requested:

      i. Group quiz?

      ii. Math examples of (because I had said those were the topics of the quiz) and info about each concept:

         A. Hubble’s law (observables)

         B. $E = mc^2$

         C. Blackbodies

      iii. Run through math example of each equation: Wien’s Law, Stefan-Boltzmann Law

      iv. What are expectations for research project?

      v. Magnitude–absolute versus generic

      vi. Redshift

   (d) General concerns about the class:

      i. Go slower with math concepts and more in-class examples

      ii. Complicated homework

      iii. Question that reading quizzes are too complicated?

      iv. In-class math group work.

      v. Go over some of the homework problems for clarification: plotting, finding constants

      vi. Is this class really an intro class?

   (e) My response

      i. I’m testing for an improvement in ability, of math as well as comprehension.

      ii. Come to office hours (or communicate with me) or I have no pity for you.

iii. I want everyone to learn all the connections between the various topics.
iv. Reading quizzes are quizzes about everything. Be clear. Be prepared.

4 What to do better

1. Don't mention things even in passing that you are not prepared to discuss further.
2. Talk about observations and physics (which is the prime goal)
3. Adrian suggested doing in-class worksheets, which shortly afterwards, the students also suggested.
4. Set late policy
5. Cover blackbody radiation physics better: why atoms move with range of velocities, how it's an idealized model, where it applies.
6. Discuss flux and surface area stuff
7. Drop lowest (two) quiz grade (makes it easier if people have to miss)
8. Actually teach how to read plots and fit lines
9. Explain better how though there are 2 protons and 2 neutrons in the nucleus of helium, there is binding energy that makes the two masses unequal.
10. Need to make clear why students are doing steps in homework problems (*i.e.*, we are going to compute the maximum lifetime of a star assuming it can convert all of its hydrogen to helium).
11. Keep pushing them hard earlier and be nicer to them at the end.
12. Be more explicit in the syllabus; the policy should be "you miss a graded item, your grade suffers unless otherwise stated."
13. Tell students that they have to learn to read. If something doesn't make sense, they need to figure out why, not ignore it. They also need to follow directions if they want the chance to maximize their points.
14. Actually read the notes you worked to put together.
15. Put lecture notes on the web.
16. Consider just letting students come or not; so long as they know when the quizzes are and what's expected from non-attendence.
17. If no textbook in future, students will need general resource for questions; some need math examples to follow.

5 Overview of Cosmology

1. To-do: have students sign-in (by name on roster) and add email address.
2. (Keep notes on students on roster.)
3. Discuss class rules of engagement
   (a) Everyone is expected to participate. The instructor may call upon students who have not contributed in awhile.
   (b) Everyone will be respectful and receptive to others' contributions.
   (c) Feel free to ask questions at any time. The instructor will endeavor to address them in reasonable fashion.
   (d) No one is glued to his/her seat. Feel free to move as necessary. Please choose seats forward and center of lecture hall.
   (e) Same applies to the instructor. "And help me *keep us on time*. Give me a five minute warning." (Howie Haber story.)
4. To-do: hand out introductory survey.
   (a) Name:
   (b) Years at UCSC:
   (c) Are you a transfer student?
   (d) Major:
   (e) College-level math and science classes taken (not course numbers but broad description):
   (f) What has been your favorite course at UCSC? If nothing, what course are you excited to take in the future? Why?
   (g) What course have you liked the least? Why?
   (h) What do you want to gain/learn from this class?
   (i) If you were at Twinkie, what would you be filled with? (First impulse, don't over-think.)
5. "1) What is cosmology?" (discussion)
   (a) Instructor's goal: set the tone of the course; engage the students; focus on the course; formative assessment.

(b) Instruct class to pair up, preferably with a stranger, introduce, discuss "what is the definition of *cosmology*?", and record thoughts on paper.

(c) Ask for volunteers to share; facilitate toward class definition:

   i. *Merriam-Webster* OnLine: "2: a branch of astronomy that deals with the origin, structure, and space-time relationships of the universe".

   ii. Key points: study (*logos*) of *cosmos*: large-scale structure and evolution (cutting out the stuff smaller than a galaxy as much as possible).

(d) *Be careful not to jump the gun and say too much before the next question.* Students become fixated.

(e) "2) What topics or objects are studied under cosmology?"

   i. Instruct class to individually reflect and record on what topics or objects fall under the new working definition of cosmology.

   ii. Ask for everyone to share (everyone must contribute even if to repeat what has been said).

   iii. Record (and tallying repeats), vaguely organizing by size scales.

   iv. Ask class if they see recurring themes or seemingly important topics.

(f) Hand out syllabus and discuss plans for course.

   i. Say "Anyone without consistent and/or ready access to email or internet must talk to me."

   ii. First reading distributed but future readings will be your responsibility. (Note: **quizzes typically about readings.**)

   iii. Several assignments detailed in syllabus, so refer to that. "It is your responsibility to turn in assignments. Dates and times are given."

   iv. You can check out the first homework assignment online to get a sense of that aspect of your grade.

   v. Please come to office hours with whatever questions/comments/concerns you have.

   vi. I will be grading on a curve. I try to be very explicit about what I will be grading on.

   vii. Homeworks seem large because I try to give as much info as possible (since we don't have a book).

6. *Be careful not to jump the gun and discuss science when discussing syllabus.*

7. "3) What is science?" (discussion)

   (a) Instructor's goal: assessing if students improving reflecting, recording, and sharing; assess ideas of science. **Prefacing the inquiry.**

(b) Instruct students to reflect and record "what is the purpose of science?" and "how is science done?".

(c) Ask for volunteers to share some ideas and record on the board.

(d) Share working definition and methodology:

   i. Instructor defines science: body of empirical (observable) knowledge about natural phenomenon.

   ii. Instructor defines "scientific method": iterative, cyclical process of asking a question, designing a way to investigate the question, developing an answer to the question, testing the answer, repeat as necessary.

(e) Also acknowledge that course is focused on the scientific process *doing* but there are other issues: ethics (partly addressed by requiring acknowledgment of collaborations); designing experiments; funding; presentations.

8. Introduction to astronomical observing

   (a) Concept question: why do astronomers use telescopes?

      i. Improvement over the human eye.

      ii. Sensitivity (increase light-gathering ability).

         A. Scales with area (proportional to diameter squared).

      iii. Resolution (amount of details; roughly magnification).

         A. Scales with inverse diameter directly.

      iv. Telescope structure

         A. Demonstration: cardboard telescope.

         B. Diagram: basic reflector; uses **mirrors**.

         C. Telescopes geared (primarily by reflection properties) towards different wavelengths

         D. Demonstration: bouncy balls on different texture surfaces to show how the wavelength of light and the smoothness of surface matters to design.

      v. Wavelength (Electromagnetic spectrum)

         A. Basic understanding that there are many energies/wavelengths/frequencies of radiation.

         B. Radiation is used interchangeably with light in astronomy, unfortunately.

         C. Indicate that atmosphere reflects/absorbs most harmful radiation.

vi. Telescopes in space.
    A. Above the weather (also why telescopes on mountains).
    B. Above the distorting effects of atmosphere (also why telescopes on mountains).
    C. Above the radiation-absorbing/reflecting effect of atmosphere.

(b) Charge-couple devices (CCDs)
  i. Activity: coded-image handout and read-out.
  ii. **Quantitative** measure of what telescope observes. (Astronomers used to draw what they observed.)
  iii. CCDs found in digital cameras.
  iv. CCDs are "blind." Use filters (and different telescopes) to separate details.
  v. Effects of exposure time on how images look and how measurements are affected (saturation).
  vi. SNAP NIR CCD image: 1500 nm in diameter; chips include 2048 $\times$ 4096 pixel (15 μm).

9. **Break** (11:18 PM)

10. Blackbody radiation

(a) Consider the nature of what astronomers are observing: light.

(b) All objects only reflect and/or emit light.

(c) Emitted light is due to temperature or chemical composition.

(d) Demonstration: light source and gratings.
  i. Incandescent bulb; handheld gratings; gel filters.
  ii. Observe how white light contains all colors.
  iii. Observe how filters block light of certain colors.
  iv. Observe how the bulb is also hot (infrared).

(e) Focusing now on the (range of) light/radiation due to temperature (continuous spectrum; thermal radiation; blackbody radiation).

(f) Due to atomic motions:
  i. Diagram: atomic structure.
  ii. Colliding atoms boost electrons to higher energies, which then release that same energy.

iii. The hotter the object, the faster the average velocity of the atoms; the more energetic the average collision and the more frequent the collisions; more radiation and of higher energy
iv. Diagram: atomic motion (velocity) in proportion to temperature.
v. Concept question: what kind of blackbodies do you see in everyday life?
vi. Diagram: differences between peak wavelength.

(g) Properties of blackbody radiation:
i. Idealized object.
ii. Wien's displacement law: $T\lambda_{max} = 2.898 \cdot 10^6 nmK$
iii. Stefan-Boltzmann law: $j = \sigma T^4$

11. Conclusion

(a) Emphasize that these are the **main points** the students should remember.
(b) Handout: make a hand out of conclusions.
(c) This is a participation-based class.
(d) Cosmology for AY5 is the study of the large-scale structure and evolution of the Universe.
(e) Science is organized around observations, and the scientific process is iterative and cyclical.
(f) All astronomers have is "light" (radiation) to observe.
i. Telescopes and CCDs enable astronomers to make quantitative observations.
(g) Blackbody radiation is an idealized model that describes an object's emitted radiation solely by its temperature.

12. Notes for next time:

(a) I will not be teaching (or in attendance).
(b) Ryan Montgomery will be in "charge."
(c) (No office hours this week.)
(d) Special instructors are coming in to lead an inquiry.
(e) Students will be emailing abstract/summary/reflection by Saturday.
(f) Highly recommend not dropping class until finish inquiry Friday. Drop deadline is Friday June 27th for Summer Session I.

13. Galaxy image
    (a) Instructor's goal: pre-assessment for galaxy inquiry.
    (b) "4) What do you observe?" *in this image and not generally based on lecture.*
        i. Tell them it's a galaxy.
        ii. Ask them to note interesting aspects of the image (at least two not mentioned out loud in discussion).
        iii. Tell them to write questions separately (because questioning is the second step to observing something).
    (c) Collect handout.
14. Critique of lecture, 2008:
    - Ended 45 min. early. Should have not excused but:
        - Math review (optional, for those who need it): significant figures, scientific notation, dimensional analysis, equation manipulation.
        - Fun examples: calculate how much you make picking up pennies; how much one would have to make for Bill Gates to be interested; converting dollars per gallons to euros per liter and discuss what it *means* (the new number is not what Europeans pay but what we pay and Europeans wish they paid).
        - Discuss "What it means to be a scientist?" Talk about grants and how telescopes operate.
        - Give presentation demonstration: good, bad, ungly; texty powerpoint, bad body language, volume, speed, up-speak (tool, not habit); what can save you (great slides); how I rate myself (middle).
    - I wasn't organized.
    - I didn't field questions well.
    - I put demos in wrong place, had no script for them, and let everyone just play.
    - How to field diversity of levels?!

6 Galaxy Inquiry

1. Broader course goals:

   (a) Radiation is all astronomers have to study.

   (b) A galaxy has components: stars, gas, and dust.

   (c) Students should understand the information contained in an astronomical image.

2. **Debrief**: perhaps Sunday June 29th so I can be prepared for Monday.

3. Gathering images

   (a)

7 Light: Properties and Information

Materials: gratings, gas emission tubes, USB spectrograph, dichroics, gel filters, overhead projector filters, blacklight.

1. First address any residual items from the Galaxy Inquiry.
   (a) Comments from written summaries.
   (b) Ask if students want to ask or share anything.
   (c) Tell them to remember what they like and don't like; to put it in the final writing assignment.
2. Couch this lecture as a story to understand astronomical objects.
3. Consider having assigned students to read website *Multi-Wavelength Milky Way* (http://mwmw.gsfc.nasa.gov/).
4. Display an image of a galaxy group with different color galaxies.
   (a) Ask what the students see in the image. Elicit comments about:
      i. Three galaxies of different morphologies. What are the types?
      ii. There are differences in color. What do the colors mean with respect to temperature? Composition? How are the colors made visible?
      iii. There are stars in the image. The stars are foreground. (This will not have become clear from the inquiry.)
   (b) What astronomers see in this image (heavily reliant on prior knowledge):
      i. Optical image (mostly) of region of sky " in Leo."
      ii. Hickson Group 44: "This group of three galaxies in the constellation Leo (AKA the Trio in Leo) is composed of two spiral galaxies (NGC 3190 at the center of the image, NGC 3187 at the left of the image). The non-descript elliptical galaxy NGC 3193 is located at the left side of the image. These galaxies are members of Hickson Compact Group 44, compiled by Canadian astronomer Paul Hickson. These groups are thought to have interacted in the past (as have most galaxies) and NGC 3190 exhibits some traces of a past interaction with NGC 3187." (SDSS Archive of the Week website.)
      iii. Four members within 16.4', 50-60 MLy at 1500 km/s. Fourth member (ring) spiral is off the image to the lower right (southwest). (http://www.skyhound.com/sh/archive/mar/HCG_44.html)

iv. Three galaxies: elliptical, edge-on spiral, irregular/spiral galaxy that's star-bursting.
v. Group of galaxies because not dominated by ellipticals and not that many galaxies.
vi. Foreground stars but not many so nearby group.
vii. Interestingly, the brightest foreground star is red, so probably cool giant. (Or could be artifact of observing times.)
viii. Imaging artifacts: diffraction spikes on bright stars; any internal reflection of galaxy (like M87, from inquiry).

5. Located in Leo
   (a) Introduce them to Google sky.
   (b) Constellations started out as patterns of stars, but now they are "counties" of the sky.

6. Optical wavelengths
   (a) Reminder of the range: $\approx$ 400–700 nm.
   (b) Inform them that $\approx$ or any $\sim$ indicates approximation.
   (c) Explain filters again.
   (d) **Demonstration**: filter bandpasses with overhead projector and gel and dichroic filters.
      i. 1D spectrum may be hard to understand
      ii. What is the source? White light.
      iii. What is the "image"? Rainbow
      iv. *Demonstrate* the slit effects.
      v. Make a "slit" to make "image" more defined. Slit direction depends on grating direction. Want them to be parallel.
      vi. "Mr. Light bends towards Mr. Thick." Can draw grating and show how end up with 2 mirrored rainbows on either side of slit.
      vii. Can show with laser pointer where the beams end up.
      viii. Show difference between dichroic and gel filter used during inquiry.
      ix. Can show contiguousness with black light (though black light is different physics!)
   (e) SDSS actually have some near-UV and near-IR bands.

7. Explaining how astronomers know what they know. (Electromagnetic radiation revisited.)

8. Disclaimer: galaxies are composed of parts (stars, gas, dust) and the whole is influenced by the parts but every characteristic of the parts is applied to the whole.

9. Spiral with star formation:

   (a) Stars are bright, blue, hot, (young): 100 $j_\odot$, $\lambda \approx 490\,\text{nm}$, 10,000–30,000 K, (Myr).

   (b) Pleiades image is example of what's in the galaxy.

   (c) Caveat: whole galaxy is not bright (it depends on the number of stars).

   (d) Caveat: another projection and the galaxy may not be blue.

   (e) Caveat: star forming regions have a lot of cold molecular gas.

   (f) (Caveat: whole galaxy may be old; like cells in our body—they're renewed but we aren't.)

10. Blackbody radiation laws

    (a) Wien's law: $\lambda = 2.898 \times 10^6\,\text{nmK}T^{-1}$

    (b) Stefan-Boltzmann law: $j = \sigma T^4$ where $\sigma = 5.67 \times 10^{-8}$ J s^{-1} m^{-2} K^{-4}.

    (c) Switch to flux (not j) and the energy emitted per second per unit surface area of the blackbody.

    (d) Emphasize that the temperature is the physics of interest; λ is the observable; flux is a tool.

11. **Talk about significant figures.**

12. Applying laws to Star-forming spiral

    (a) Evaluate the statement: "Up to 100 times $\text{j}_\odot$": $j = \sigma T^4$
    $L_\odot \equiv \sigma T_\odot^4$
    $L_\star = 100 L_\odot = \sigma T_\star^4$
    $100(\sigma T_\odot^4) = \sigma T_\star^4$
    $100 T_\odot^4 = T_\star^4$
    $100^{0.25} T_\odot = 3.16 T_\odot = T_\star$
    $3.16 \cdot 6000K = 19,000K = T_\star$
    I can use luminosity because brightness is proportional to luminosity ($j = L/area$).

(b) Evaluate the statement: "Blue $\lambda \leq 490\,\text{nm}$" $\lambda = 2.898 \times 10^6\,\text{nmK}T^{-1}$
$490nm = 2.898 \times 10^6\,\text{nmK}T^{-1}$
$T = 5900K$
$T > 5900K$
But the "blue" is an *optical* constraint. Actually, peak is UV $\lambda \leq 290\,\text{nm}$ ($T = 10,000\,\text{K}$). (Show curves.) **Blue light dominates optical.** (See slope.)

(c) Evaluate the statement: "Hot 10,000 K–30,000 K"
$j = \sigma T^4$
$j = 5.67 \times 10^{-8}\,\text{J s}^{-1}\,\text{m}^{-2}\,\text{K}^{-4}(30,000K)^4$
$j = 4.59 \times 10^{10}\,\text{J s}^{-1}\,\text{m}^{-2}$
$j_\odot = 6.25 \times 10^7\,\text{J s}^{-1}\,\text{m}^{-2} = 7.35 \times 10^7\,\text{J s}^{-1}\,\text{m}^{-2}$
$j = 734 I_\odot = 625 j_\odot$
What does this mean?! It's a brightness or *flux* (luminosity per unit area; remember, J/s = Watt). The blackbody surface is radiating that number of Watts per square meter. (Note: two values of $j_\odot$ come from $j = L/(4\pi R^2)$ and the other from Stefan-Boltzmann's Law.)

13. Dust: reddening

   (a) Dust is larger than molecules and smaller than rocks. H_2 is 0.074 nm (Wikipedia). Largest dust is 0.1 mm (10^5 nm).
   (b) Dust grains affect wavelength of light on the order of the same size. Most often, in astronomy, light is reddened through the dust but there are also reflection nebula.
   (c) Light is reddened or extinguished (less light).
   (d) Explains sunsets and why the sky is blue (N_2 and O_2). (Could be a calculation/problem to find what atmospheric grains needed to make sky red.)
   (e) Think of the recent fires making the sun look redder even when it's high in the sky.

14. Dust: scattering

   (a) Conservation of energy: blue light doesn't just disappear.
   (b) It does contribute to the heating of the grains.
   (c) But grains scatter (and reflect) light, preferentially the blue light, out of the *line of sight*. Geometry!
   (d) Witch Head Nebulae is "reflection nebula" and the OB association (Rigel in Orion) off to the right.

15. Dust (red) blackbody
    (a) Light is reflected but also absorbed. *Reprocessing.*
    (b) Again, since we have a thermally radiating source, we can use blackbody model to figure out temperature, peak wavelength, energy flux.
16. Other reasons for red light.
17. **Break** (11:10 AM)
18. Elliptical: properties of majority of stars (and caveats
    (a) Dim (1/16th brightness of sun). Caveat: generally elliptical galaxies have more stars and are brighter.
    (b) Red (625 nm $\leq \lambda \leq$ 740 nm). **Red light dominates the optical but peak is in the IR.** Caveat: they may have blue cores; leftover from recent merger. Also emits at other wavelengths.
    (c) Cool (T $<$ 3500 K). Caveat: may have warmer components, like in the gas phase.
    (d) (Old, Gyr timescale. Caveat: may have younger components, like the recent merger.)
19. "Yellow" or green blackbody: our Sun
    (a) Addressing because of some confusion during inquiry. The human bias in eyeball observing.
    (b) Our Sun's peak wavelength is yellow-green.
    (c) Our Sun's total visible color is defined to be white light.
    (d) So white light has more yellow-green in it than other colors.
    (e) Human eye (and most all life on Earth) evolved to deal with our particular Sun's light.
    (f) Chlorophyll is green because that is the light it doesn't want (hence, reflects).
20. Not all radiation is blackbody radiation: types of spectra
21. All objects either emit light, absorb light, reflect light, or some combination.
    (a) Emphasize the absorbing and emitting due to composition.
    (b) Say that object doing more than one of these is complicated.

(c) Reflected light is what everyone has most experience with. (Discussed chlorophyll earlier.

22. **Demonstration**: emission tubes; Na would have been nice; need USB spectrograph

23. Three types of spectra

    (a) White light thermal source (all colors)

    (b) Viewed directly is blackbody continuous spectrum.

    (c) Viewed through a cool (chemical) gas, see absorption spectrum. Has to be cool so it's not a blackbody itself. *We're not talking about reddening.*

    (d) View just the (chemical) gas, see emission spectrum. *We're not talking about reflection.*

    (e) Reflection/scattering, reddening are other processes that could happen, but we're idealizing the situation.

24. Why Spectra?

    (a) See details of object's light.

    (b) As if we had used narrower and narrower filters.

    (c) Stellar spectra shown is mix of blackbody and absorption spectra.

25. Matter and atomic energy levels

    (a) Matter composed of atoms.

    (b) Atoms have nucleus and electrons in quantized orbital clouds.

    (c) No in-between clouds, discrete.

26. Changing energy levels

    (a) Electron will accept energy from photon and move up in the world.

    (b) But debt may be called in and the electron will move down in the world.

    (c) These two processes define absorption and emission spectra.

27. Energy in electron energy levels

    (a) Discuss change in energy levels defining wavelength and visa versa.

(b) Speed of light (and hence wavelength and frequency) may change depending on medium. We will usually consider vacuum energies. (But the superluminal jet in M87 is an artifact of the medium.)

(c) My examples are UV transitions.

(d) Example: Ionizing hydrogen
$E = h\nu = hc/\lambda$
$13.6eV = 4.136 \times 10^{-15} eV \cdot s \cdot 3 \times 10^8 m/s/\lambda$
$13.6eV = 1.241 \times 10^{-6} eV \cdot m/\lambda$
$\lambda = 1.241 \times 10^{-6} eV \cdot m/(13.6eV)$
$\lambda = 9.124 \times 10^{-8} m = 9.124 \times 10^{-8} m \cdot 10^{10} \mathring{A}/m$
$\lambda = 912.353\,\mathring{A}$

(e) Example: Lyα
$E = h\lambda = hc/\lambda$
$E_{Ly\alpha} = 4.136 \times 10^{-15}\,\mathrm{eV} \cdot s \cdot 3 \times 10^8\,\mathrm{m/s}/(1.2156701 \times 10^{-7}\,\mathrm{m})$
$E_{Ly\alpha} = 10.2067\,\mathrm{eV}$
$E_{GS} = 13.6\,\mathrm{eV}$
$E_{GS\to 1} = 10.267\,\mathrm{eV} + 13.6\,eV = 20.8\,\mathrm{eV}$

28. Emission line spectra

(a) Chemical fingerprint.

(b) Bright lines with no other source to make rest of rainbow.

(c) Gas tubes take essence of color (like galaxies and their stars).

(d) Compact fluorescent bulb uses vaporized mercury to excite a phosphor that then fluoresces. Higher energy efficiency because discrete colors. (Shown energy and wavelength connected.)

(e) Elements are complicated...

(f) LED is light-emitting diode and form of electro-luminescence. The color comes from the composition of semiconductor.

(g) Emission spectra of various bulbs (http://web.ncf.ca/jim/misc/cfl/index.html)

29. Absorption spectrum: the inverse

(a) Sun in absorption (as well as all stars).

(b) The image is just one long spectrum broken up for display.

(c) Also chemical fingerprint.

(d) Total color looks like blackbody (usually).

(e) Helium discovered in the Sun's spectrum ('hellos').

30. Stellar spectra
    (a) The temperature of the hot body center determines the blackbody peak wavelength and therefore the color in stars.
    (b) But the temperature also regulates what elements or even molecules may exist in the cooler photosphere.
    (c) More about stars next time.
    (d) The image is of many spectra, blue to red aligned.
31. Properties of Light conclusions:
    (a) All objects either emit, absorb, or reflect light (or some combination).
    (b) Blackbody (AKA thermal, continuous) radiation is due solely to object's temperature. (Equations: Wien's Law and Stefan-Boltzmann's Law)
    (c) Emission and absorption spectra inform about chemical composition object. (Equations: $E = h\nu$)
    (d) Astronomers use spectroscopy to measure details of object's light (and from that it's physical description.)
32. Class notes
    (a) Optional math review schedule when?
    (b) Advanced math review or lesson for others? For those who want math challenge, we can learn about order of magnitude. Should not let higher level students not improve in general.
    (c) Tell me how the level of math taught in class is so I can adjust to best level for class.
    (d) Reading on "Misconceptions about the Big Bang" due next time. Recommended that everyone print it out and bring it.
    (e) There will be a quiz on the reading and on anything covered in class so far.
33. *Ended 25 minute early, forgot second 5 min break*
34. If extra time:
    (a) Shoed rest of post-inquiry lecture.

(b) Multi-wavelength analysis of galaxy group NGC4410 (http://www.etsu.edu/physics/bsmith/research/n4410.html).

(c) Multi-wavelength M81 (http://seds.org/MESSIER/more/m081_sst.html)

(d) Multiple telescopes with myriad of characteristics.

(e) Multi-wavelength trace different regimes: high vs low energy. UV light and IR (re-processed UV light). Etc.

(f) Galaxy mergers and evolution.

8 History of the Universe I

1. Class Notes

    (a) Quiz on class-thus-far and "Misconceptions about the Big Bang" 15 min. (I may choose to give extra 5 min.)

    (b) Problem set #1 "Scale Models in Astronomy" due Monday in class. I'm docking points for late work. I want it legible. Today and tomorrow are only office hours available (no class Friday).

        i. **Submit a map of the top of campus for #3c. It'll be easier.**

    (c) Problem set #2 "Energy History of the Universe" will be posted soon. I'll send out an email.

    (d) Reminder: you need approval of the article for the final presentation. (Must have it before July 16th.)

    (e) No class Friday. Happy 4th.

    (f) How is internet access going?

2. Discussion about "Misconceptions about the Big Bang"

    (a) Start with questions about article.

    (b) Need to couch the full story in whatever they know.

    (c) Tell them that through discussion we're going to try to get everyone on the same page.

    (d) Ask everyone to participate. Forewarn them that they may be called on. (Participation is a grade.)

    (e) Tell them to get it out of their heads to care about what anyone but me thinks.

    (f) Prompts:

        i. What was the Big Bang? (Explosion of everything: space, time, matter, energy, physics)

        ii. What is the evidence for the Big Bang? (CMBR, expansion)

        iii. What did the Big Bang explain versus what did it predict? Both evidence but prediction holds more weight. (CMBR was prediction. Expansion was matched observation.)

        iv. What are the facts about the Big Bang from the article?

        v. What are the misconceptions the article addressed?

vi. What are the equations discussed in the article? They said in words what mathematical symbols could say.

3. **Break** (11:40 AM)

4. State: this is going to be a tough lecture. Things are intricate, subtle, and mind-boggling. *Students need to state early and often when they are confused.*

5. Concept question: is the Universe static? (*i.e.*, do objects move in the Universe?) How do we know this?

   (a) Let them know that the obvious answer is indeed correct; don't be afraid to say it.

   (b) We move. We know the Earth and planets move. Astronomers know the Sun orbits the center of the Milky Way Galaxy. Lots of evidence of motion.

   (c) Also, jumping the gun, yes, we observe the recession of distance galaxies. Hubble discovered this in 1929.

   (d) But there's also the fact that if nothing was moving, the Universe would collapse on itself.

   (e) Introduce Newton's Law of Universal Gravitation and the constant.
   $\hat{F}_{12} = \frac{GM_1M_2}{r_{12}^2}\hat{r}_{12}$
   Read "Force of 2 on 1 along the direction between them." Sometimes a negative sign floats around. It's all about mental picture. It is attractive but as shown to the students, they wouldn't know that.

      i. Have the students discuss in words what the equation means.

      ii. Point out the units of force. (Wary of physics.)

      iii. Probe the students' understanding:
      "If I double the distance, how does the force change?"
      "If I double the distance and both the masses?"
      "How does the force of Earth's gravity on me compare to the force of Earth's gravity on you?"

   (f) If your really want a static Universe, then have to have it be infinite and roughly uniformly populated to balance the attractive force of gravity. Take time to discuss this.

6. Concept question: is the Universe infinite in space and time? How do we know?

   (a) Olber's paradox

   (b) Why is the sky dark?

(c) Already shown that if we wanted a static Universe, we would need it to be infinite in space and roughly evenly populated.

(d) So if it wasn't just set in place some finite time ago, there would have been enough time for all starlight to reach us, and blind us during the night (and day).

(e) Classic analogy is looking at a forest of trees. If it were infinite, you'd always see a tree.

7. Big Bang Theory: solution to problems already addressed and for problems to be discussed.

   (a) What does theory mean in science?

   (b) In science, a theory is a respected word. It means that the explanation(s) or model(s) have proven correct repeatable, with a variety of experiments, and is considered to be *the* right answer, but science must allow for all the votes to be cast.

   (c) Roughly, it scales with the complicatedness of the idea

8. Brief History of Big Bang

   (a) 1916: Einstein publishes his General Theory of Relativity, which allows a *non-static* cosmological solution. Einstein discovered this in 1915. He added the "cosmological constant" to enable a static Universe. Ironic that it has come back to be true and used for a completely different purpose.

   (b) 1920: Harlow Shapley and Heber Curtis debate how big the Universe is. Shapley believes its only the Milky Way, and the Sun is not in the center. Curtis believes there are other galaxies but the Sun was at the center our (according to Curtis, small) galaxy.
   http://antwrp.gsfc.nasa.gov/diamond_jubilee/debate_1920.html

   (c) 1922: Alexander Friedmann formulates expanding-Universe solution from GR

   (d) 1925: Edwin Hubble (100" Hooker Telescope at Mount Wilson Observatory) proves "spiral nebulae" are actually galaxies. By looking at Cepheid variables in Andromeda.

   (e) 1929: Hubble discovers recession of galaxies. Hubble's law: $v = H\,d$.

   (f) 1965: Arno Penzias and Robert Wilson from Bell Labs, NJ, accidentally discover CMBR, as predicted by Big Bang theory.

9. History of the Universe figure (and handout):

(a) This is the bottom portion we're going to cover now and on Monday.

(b) The times are uncertain (comparing across sources, it's typically ± 1 in the exponent of time in seconds and temperature.

(c) Wikipedia, *The Cosmic Perspective*, Inflationary Big Bang timeline (http://aether.lbl.gov history.html)

10. Beginning of Everything: misconception addressed

    (a) Big Bang was creation of **everything**: space, time, physics, energy, etc.

    (b) Expansion is due to space upon which we're riding, expanding.

9 History of the Universe II

1. Blackbody radiation revisited
   (a) Due to vast majority of quizzes reflecting that this is not understood.
   (b) Blackbody radiation is **continuous**.
   (c) Peak wavelength is a defining characteristic and related to temperature.
   (d) But more light is more light. Hands down (for blackbodies).
   (e) *This will be very important for early Universe physics.* Because the shape and height relates to the energy in the photon "field."

2. Ask for one or more residual questions from last discussion and lecture; will address

3. Ask for one or more new understanding.

4. (*Referred too much to "In a few slides" or "later", which indicates bad organization; don't say or put someehting out there that I can't elaborate on (e.g., luminosity distance.)*)

5. (*Address how these times are known; discuss nature of models; state that exponents are* ± 1 *in the first three minutes.*)

6. Timeline of Early Universe figure (handout)

7. Planck Era (epoch):
   (a) Up to 10^{-43} s and defines the limit to what our science can understand.
   (b) We have no "Theory of Everything" which combines all four fundamental forces. Such a theory is also known as "supersymmetry," "superstrings," "supergravity," or "quantum gravity."

8. Fundamental Forces of Physics
   (a) Strong nuclear force:
      i. exchange particle is the gluon
      ii. It's 10^{38} times as strong as gravity
      iii. It only works over the size of the nucleus 10^{-15} m.
      iv. It's what holds a nucleus together.
   (b) Electromagnetic force (Coulomb's force):

i. Exchange particle is the photon (wave-particle duality).
ii. It's 10^{36} times as strong as gravity.
iii. It has an infinite range, like gravity.
iv. But it can be shielded, unlike gravity.

(c) Weak nuclear force:

i. Exchange particles are W, Z bosons. Bosons defined to obey Bose-Einstein equations, can occupy the same state, and have integer spin. Other bosons maybe composite (e.g. ^{4}He, but W,Z (and other exchange particles) are fundamental.
ii. It's 10^{25} times as strong as the gravitational force.
iii. It's range is 10^{-18} m.
iv. It's responsible for radioactive decay.

(d) Gravity

i. The undiscovered graviton is the exchange particle.
ii. It is 10^{-38} times the strength of the strong nuclear force.
iii. It's range is infinite, and nothing can stop it; no "anti-gravity" but there is still dark energy...

9. Grand Unified Theory Era

(a) $\approx 10^{-43}$–10^{-35} s
(b) Ends with $T = 10^{28}$ K.
(c) Then strong nuclear force separates from electroweak force
(d) Suspected to be cause of inflation.
(e) These transitions are like phase changes in chemistry (think of the phases of water).

10. Inflationary Era (or Inflation)

(a) **Rapidly increase the size and hold everything else constant.** So density decreases, technically temperature increase (compared to what it should have been), push everything outside light cones (though they can retain information of each other).
(b) $\approx 10^{-34}$ s–10^{-32} s but remember ± 1 in exponents.
(c) Universe stops dropping in temperature, stays at 10^{27} K. This is essentially like re-heating. Since it's supposed to be expanding and cooling.

(d) The expansion is faster than the speed of light. Basically 1 m in 10^{-34} s is 10^{23} c!

(e) Isotropic and homogeneous expansion (nothing lopsided). Emphasize these words as re-occurring. "Isotropic" is the same values in all directions and "homogeneous" means uniform in composition and structure.

(f) (*Disjoint here becuase isotropic and homogeneous should come in with CMB discussion.*)

(g) **Quantum fluctuations blown up to large scales to eventually become structure in the Universe.**

(h) Regions originally in causal contact pushed outside each other's observable Universe.

(i) Universe flattened (spatial density about critical).

(j) (*Be careful not to be too repetitive with the next causal contact slides. Stay focused.*)

(k) Causal contact figure: light cones and how we know information about both regions before they do but they seemed to have "talked," otherwise how would they be so similar. *Age of Universe and (finite) speed of light defines observable Universe.*

(l) Causal contact and inflation figure: the seemingly un-communicating portions of the Universe were in contact before inflation. Inflation took everything that was in equilibrium and pushed it all out and away very rapidly and very uniformly. Isotropy and homogeneity.

(m) Flat Universe figure: means that angles of a triangle sum to 180 degrees. It's tricky to think in terms of flat spacetime and the future of the Universe. It's not synonymous to be flat and to have critical density when there's a vacuum energy Λ. Accelerating Universe could be flat, open, or closed. walk back to our starting location.)

(n) Critical density figure: (taste of what's to be discussed.) Closed Universe is re-collapsing. Flat Universe is expanding forever. Accelerating Universe can be any shape. *Carefully explain.*

11. Isotropic and homogeneous:

(a) (*Need large-scale structure plot; hard to do without it.*)

(b) Is the Universe isotropic and homogeneous?

(c) *Isotropic*: uniform in all directions

(d) *Homogeneous*: same composition throughout

(e) Elicit the students to comment

(f) But it's obvious that we are not the same.

(g) However, at larger scales, with a bigger field of view, we do see the Universe is isotropic and homogeneous.

(h) And the biggest evidence for that is the CMB

(i) The Universe couldn't be perfectly smooth due to quantum mechanics.

(j) Then inflation made it possible that these quantum fluctuations stretched to be structure we see today (the seeds actually).

12. Electroweak Era

    (a) $\approx 10^{-32}\,\mathrm{s}$–$10^{-11}\,\mathrm{s}$

    (b) Ends with $T \approx 10^{15}\,\mathrm{K}$ when weak nuclear force separates from EM force

    (c) Fundamental particles gain mass from Higgs mechanism. I don't fully understand this but since this is first time that massive particles exist, they must gain mass.

13. Particle Era

    (a) $\approx 10^{-12}\,\mathrm{s}$–$10^{-3}$: beginning of when physics can be understood because particle accelerators have matched these conditions and we live in a time when all fundamental forces are separate.

    (b) Ends with $T \approx 10^{12}\,\mathrm{K}$ when it's too cool to spontaneously produce particles.

    (c) Amount photons is about the amount of particles. More energy is in the photons.

    (d) At $\sim 10^{-4}\,\mathrm{s}$, quarks form into neutrons, protons, etc. And it's these particles that make up us.

14. Introduction to Particle Physics (a necessary evil)

    (a) Particle accelerators can be considered laboratories for astrophysics on Earth. They are creating conditions similar to the early Universe.

    (b) They work by slamming particles together at very high energies and detecting what happens and matching it to models or visa versa.

    (c) Standard Model of Particle Physics figure:

i. Quarks are the indivisible units of matter like protons and neutrons. Scientists once thought it was the atom, then the nucleus, then the proton/neutron. But now it's quarks. Maybe someday strings.

ii. Baryons is the term for ordinary matter. What we're made of. They are combinations of quarks. This is like chemistry. But instead of elements making up molecules, it's quarks making up baryons.

iii. Neutrinos come up a lot in astronomy. They're typically by-products of reactions (like heat is in chemistry). Supernovae are probably helped by neutrinos. Neutrinos are streaming through us right now but they barely like interacting.

iv. Anti-particles exist for everything. But they mostly appear (and disappear) in particle accelerators. It is a puzzle why there's not more. (Get to that in a moment.)

v. Pair production: understanding $E = mc^2$.

   A. Matter and energy interchangeable

   B. I am 70 kg. I am worth 6.3×10^{18} J. 1 ton of TNT releases 4.2×10^9 J. Hence, if I could instantly and efficiently convert myself to energy, I would be worth 1.5 gigaton of TNT (or 630 H-bombs). Take that, TSA.

   C. $m_e = 0.511\,\mathrm{MeV/c^2}$

   D. $m_p = 938.3\,\mathrm{MeV/c^2}$

   E. $m_n = 939.6\,\mathrm{MeV/c^2}$

   F. $m_\alpha = 3727.3803\,\mathrm{MeV/c^2}$

   G. The energy necessary for electron-positron production (and the blackbody radiation is the source of the energy):
   $m_{e-} = 0.511\,\mathrm{MeV/c^2}$
   $m_{tot} = 2 \cdot m_{e-} = 1.022\,\mathrm{MeV/c^2}$
   $E_{tot} = 1.022\,\mathrm{MeV}$

   H. What temperature do the *particles* need to collide and turn into energy? **Demonstrating here with electrons and positrons, but they actually don't need excess energy. They will just annihilate.** Also, with higher kinetic energies, intermediate particles are typically produced and not just gamma rays.
   $E = kT$
   $k = 1.381 \times 10^{-23}\, J/K = 8.617 \times 10^{-5}\, eV/K$
   $1.022\,\mathrm{MeV} = 1.022 \times 10^6\,\mathrm{eV} = 8.617 \times 10^{-5}\,\mathrm{eV/K} \cdot T$
   $T = 1.2 \times 10^{10}\,\mathrm{K}$

I. What wavelength has this energy?
$E = hc/\lambda$
$1.022 \times 10^6\,\mathrm{eV} = 4.136 \times 10^{-15}\,\mathrm{eV \cdot s} \cdot 3 \times 10^8\,\mathrm{m/s}/\lambda$
$1.022 \times 10^6\,\mathrm{eV} = 1.24 \times 10^{-6}\,\mathrm{eV \cdot m}/\lambda$
$\lambda = 1.21 \times 10^{-12}\,\mathrm{m} = 0.00121\,\mathrm{nm}$
which are gamma-rays.

J. What would the blackbody temperature be with such a peak wavelength?
$\lambda = 2.898 \times 10^6\,\mathrm{nm \cdot K}/T$
$0.00121\,\mathrm{nm} = 2.898 \times 10^6\,\mathrm{nm \cdot K}/T$
$T = 2.898 \times 10^6\,\mathrm{nm \cdot K}/0.00121\,\mathrm{nm}$
$T = 2.4 \times 10^9\,\mathrm{K}$
which is not exactly matching the kinetic energy of the particles but close enough.

15. Blackbody radiation: source of energy

    (a) Review what is blackbody radiation?

    (b) Atoms in motion: they always move (there is no absolute zero).

    (c) Atoms and temperature: the temperature defines how fast the atoms move.

    (d) Atoms and radiation: more collisions and more energetic collisions. Here is the source of photons and extra energy to make particles or turn particles into other particles.

16. Back to the Particle era

    (a) So there is enough energy in colliding particles to make photons and enough energy in the photons to make particles.

17. Era of Nucleosynthesis

    (a) $\approx 10^{-3}\,\mathrm{s}$–3 minutes, where Goldie Locks is satisfied that everything is (briefly) just right to fuse nuclei.

    (b) Universe is dominated by radiation (that's what has the most energy.)

    (c) Ends with $T \approx 10^9\,\mathrm{K}$ when no longer able to fuse nuclei.

    (d) The resulting composition is 75% H and 25% He by mass. There is 0.01%D and some exceedingly small (10^{-8}%) amount of Li, Be. Those further reactions were not favorable.

    (e) Hydrogen and Helium figure:

i. Big Bang nucleosynthesis models match observations. More evidence for the Big Bang.
ii. There was a short window to make anything and it matters critically the temperature and the balance of nuclei production.
iii. At $T > 10^{11}\,\mathrm{K}$, neutrons and protons were made in equal numbers, even though the neutron is slightly more massive than the proton.
iv. $10^{10}\,\mathrm{K} < T < 10^{11}\,\mathrm{K}$, protons begin to outnumber the neutrons, which are slowly reacting to become protons.
v. At $T = 10^{9}\,\mathrm{K}$, the number of gamma rays decreases enough so that ^{4}He is stable (doesn't get broken apart).
vi. H is just a proton when ionized.

18. Era of Nuclei
    (a) $\approx$ 3 min–500,000 yr: everything is just an elemental stew with no objects we would recognize
    (b) Photons are trapped by the hot, dense plasma (Dark Ages)
    (c) Ends with $T = 3,000\,\mathrm{K}$ when it is cool enough for electrons to attach themselves to nuclei and stay there as full atoms. (Recombination.)
    (d) Then the photons are free to stream away as the cosmic microwave background.
    (e) Enter a new age: matter-dominated. (Sort of *Lord of the Rings*-like.)

19. CMB
    (a) Discovered in 1965 by Arno Penzias an Robert Wilson at Bell Laboratories, NJ, with microwave satellite-communication antenna.
        i. Thought it was bird poop
        ii. Concurrently, Princeton physicists were predicting CMBR.
        iii. Penzias sat next to Princeton physicist on plane ride and mutually solved each other's problem.
        iv. 1978 Nobel Prize in physics went to Penzias and Wilson
        v. 1% of snow on antenna-fed television is CMBR.
    (b) COBE (http://aether.lbl.gov/www/projects/cobe/COBE_Home/DMR_Images.html)

20. Redshift
    (a) Explain equation. State that though Hubble's law is $v = H \cdot D$ what is actually measured is redshift.

(b) A lot of astronomer's time has been tacking down Hubble's constant.

(c) CMB settles that (along with other fundamental values tied to Big Bang models).

(d) Demonstration of equations:
$\lambda_{em} = 1\,\mu\text{m} = 1000\,\text{nm}(T = 2898\,\text{K}; \text{NIR})$
$\lambda_{obs} = 1\,\text{mm} = 1 \times 10^6\,\text{nm}(T = 2.73\,\text{K}; \text{microwave})$
$z = \frac{1 \times 10^6\,\text{nm}}{1000\,\text{nm}} - 1$
$z = 1000 - 1 = 999$
$c \cdot z = H_0 \cdot D$
$3 \times 10^5\,\text{km/s} \cdot 999 = 70\,\text{km/s/Mpc} * D$
$3 \times 10^8\,\text{km/s} = 70\,\text{km/s/Mpc} * D$
$4.3 \times 10^6\,\text{Mpc} = 1.4 \times 10^7\,\text{MLy} = D$
But this is the *luminosity distance*, which is not what should go into Hubble's law. We would need the *comoving* radial distance instead, which is smaller ($D_{now} = c/H_0 \cdot \ln(1 + z)$).

(e) The two distances are about the same at low redshift but diverge at high redshift, when the effects of expansion "increase." Comoving distance is the distance between the objects *now*, if we could lay down a tape measure.

(f) The luminosity distance make Hubble's law linear, as far as we've been able to measure it. Deviations from linear at high redshift will rule out cosmological models (much like the fact that Hubble's law is linear for cz over luminosity distance rules out some cosmological models).

(g) The luminosity distance is (1+z) greater than the comoving distance, so long as the curvature is zero. (http://www.public-domain-content.com/encyclopedia/Universe/Comoving_distance.shtml)

21. Redshift and Time

(a) Speed of light is finite

(b) Therefore distances (usually redshift in astronomy) and time are related. More distant things are being observed more in their past.

22. Observing the CMB

(a) Better for microwaves to be observed in space due to partial absorption of our atmosphere as well as the fact that Earth is awash in microwaves. (But Penzias and Wilson obviously detected CMBR on Earth.)

(b) COBE satellite was the first measure of the anisotropy of the CMB. Anisotropy means now non-isotropic the Universe is. It's very smooth but there is some structure, fortunately.

(c) WMAP has given us concordance cosmology. Usually in astronomy we don't measure numbers very precisely, but with WMAP we know the age of the Universe and it's mass-energy content very well. (Of course, these are based on models of the Big Bang.)

(d) In order to see such small (1 part in 100,000) variations, have to carefully treat dipole from Sun's motion through Galaxy and the Galaxy contamination itself.

23. First Stars

    (a) $\approx 400,000\,\mathrm{yr}$ ($z \approx 1100$)

    (b) Heat and reionize the Universe

    (c) Universe complete ionized by 1 Myr ($z \approx 6$)

24. Timeline of Big Bang figure again

    (a) Just recap the sequence of events.

25. Summary

    (a) Universe has been expanding and cooling since Big Bang until the first stars light up (500,000 yr). Exception is inflation, when temperature stayed constant.

    (b) Evidence of Big Bang

        i. CMB

        ii. Expansion (though we haven't talked about that much). Typically associated with cooling.

        iii. Composition of Universe (Big Bang Nucleosynthesis): 75% H, 25% He by mass

    (c) Inflation "fixes" problem with Big Bang theory: flatness, critical density, isotropy and homogeneity. Causes unknown

    (d) $z = \lambda_{obs}/\lambda_{em} - 1$ which relates to distance and time.

26. Class Notes

    (a) **Problem set #1 due.**

(b) **No more late work accepted** unless we've pre-arranged something.
(c) Problem set #2 due Wed 16th.
(d) Article approval needed by Wed 16th.

10 Objects in the Universe: Stars I

1. Random references:
   (a) http://www.astrophysicsspectator.com/topics/stars/
2. Class Notes
   (a) 15 min "The Lives of Stars" reading quiz
   (b) Math quiz Friday. Review problem sets #1, 2, and in-class notes.
3. Questions from last time
   (a) Some were answered and some will be answered later.
   (b) And the question about using the equations should be addressed in office hours.
4. Stars (in brief)
   (a) **Mass** determines majority of characteristics like L, R, t_{age}.
   (b) Life is about **equilibrium** or balance.
   (c) Primarily composed of H, He. How much? About 75% and 25% by mass. The other elements are **metals** and play important part but not really discussed here.
   (d) The **main sequence**–which is the main focus of *this lecture*–is when H is fused into He.
5. Concept question: What is Earth's closest star? (The Sun.)
6. Our Sun
   (a) 8. light-min from Earth (close).
   (b) $L_{SUN} = 3.8 \times 10^{26}\,\mathrm{W}$, which is way more luminous than every human on Earth (6.7 trillion) holding a 200W bulb ($= 1.3 \times 10^{10}\,\mathrm{W}$).
   (c) $M_{SUN} = 1.99 \times 10^{30}\,\mathrm{kg} = 333,000\,M_{EARTH}$
   (d) $R_{sun} = 695,000\,\mathrm{km} = 109\,R_{EARTH}$
   (e) $T_{surf} = 5800\,\mathrm{K}$, which is a peak at 500 nm, yell0w-green, visible. It's 15 million K in the core.
   (f) Spectral type: G2V (G2 relates to temperature, V means main sequence.) 7.6% of stars are G stars.

(g) $t_{age} = 4.6\,\mathrm{Gyr}$.

7. Solar Structure

   (a) Photosphere is what we think of as the surface of the sun, though it's not solid and well-defined.

   (b) Chromosphere is thin skin on top at $10^4\,\mathrm{K}$, which is main source of UV (and sunburns).

   (c) Fusion takes place in the core.

   (d) Corona is what you can see during solar eclipse.

   (e) Lots of other activities but we're not discussing.

8. Solar interior

   (a) Not directly observable, though there are neutrinos which pass out fast.

   (b) It's because the interior is so dense that the photons get bounced around for 170,000 yr in process called **radiative diffusion**.

   (c) Convection is another transport of energy to the surface, and it proceeds by physically moving the hotter material around.

   (d) There are interior models based on the observations (mass, composition, etc).

9. Solar Neutrinos

   (a) Solar neutrino problem: predicted to detect 1 neutrino per day, was detecting 1 every three days. Discover neutrino oscillations.

   (b) Super-K is chamber of regular water that tries to detect glow of Cherenkov radiation, from charged particle moving faster than speed of light in the medium.

   (c) Supernova can be detected, like SN1987A (very famous) because the neutrino count bumps to 8 neutrinos in a day, which is statistically impossible from the sun.

10. Solar Mass

    (a) Measured from gravitational force and Newton's version of Kepler's 3rd law

    (b) Though M_{EARTH} negligible, we can measure it by seismology, etc.

    (c) Period is related to masses and distance.

11. Solar Composition

    (a) There are elements on the surface of the Sun.

    (b) The interior composition of the Sun is not measurable but can be matched by models.

    (c) Solar nebula composition comes from meteorites. This information must go into solar system formation models.

12. Solar structure models

    (a) All astronomer's have is *radiation* but we're very good with modeling.

    (b) Take the observables and the physics and solve the problem.

    (c) The models predict observables for the Sun that we *can* measure. (So we feel better about the predictions for other stars, where we *cannot* measure.

    (d) Predictions are: R_{SUN}, T_{surf}, L_{SUN}, t_{age}.

    (e) We can test some of the interior predictions with helioseismology.

    (f) More about models, it's like a big machine where you set some knobs and what comes out is determined by those knob settings and the commands inherent to the machine.

13. More about these "predicted" properties: L, T,...

14. Luminosity and Flux

    (a) In Stefan-Boltzmann law originally called: *energy flux density.* Flux for now.

    (b) Luminosity is a *cooling* process.

    (c) Energy hitting Earth per second:
    $F_{EARTH} = \frac{L_{SUN}}{4\pi d^2_{EARTH}}$
    $F_{EARTH} = \frac{3.8 \times 10^{26}\,\mathrm{J/s}}{4\pi(1.496 \times 10^{11}\,\mathrm{m})^2}$
    $F_{EARTH} = 1352\,\mathrm{J/s/m^2}$
    $L_{@\ EARTH} = F_{EARTH} \cdot A_{EARTH} = F_{EARTH} \cdot 2\pi r^2_{EARTH}$
    $L_{@\ EARTH} = 1352\,\mathrm{J/s/m^2} \cdot 2\pi(6.378 \times 10^6\,\mathrm{m})^2$
    $L_{@\ EARTH} = 3.45 \times 10^{17}\,\mathrm{J/s} \approx 10^{-9}\,L_{SUN}$
    which alternatively could be derived by just taking the ratio of the radius of Earth to the distance: $0.5 \cdot (6.378 \times 10^6/1.496 \times 10^{11})^2 = 10^{-9}$. **the factor of 0.5 comes from assuming the Earth is a disk and not a hemisphere.**

(d) Polaris ($L = 2200\,L_{SUN}$, $d_{Polaris} = 430 \pm 30\,\text{Ly}$, $F_{Polaris\ @\ Earth} = 4 \times 10^{-9}\,\text{J/s/m}^2$)

$$\frac{F_{Polaris\ @\ Earth}}{F_{Sun\ @\ Earth}} = \frac{L_{Polaris}/(4\pi d^2_{Polaris})}{L_{SUN}/(4\pi d^2_{Earth})}$$
$$\frac{F_{Polaris\ @\ Earth}}{F_{Sun\ @\ Earth}} = \frac{L_{Polaris}/L_{SUN}}{d^2_{Polaris}/d^2_{Earth}}$$
$$\frac{4 \times 10^{-9}}{1352} = \frac{2200\,L_{SUN}/L_{SUN}}{d^2_{Polaris}/(1\,AU)^2}$$
$$d^2_{Polaris} = \frac{2200}{3 \times 10^{-12}}\,AU^2$$
$$d^2_{Polaris} = 7.3 \times 10^{14}\,AU^2$$
$$d_{Polaris} = 2.7 \times 10^7\,AU \cdot \frac{1\,Ly}{63235\,AU}$$
$$d_{Polaris} = 427\,Ly$$

15. Magnitude
   (a) Technically, measured usually in a certain photometric band.
   (b) Brightness, intrinsic and apparent, depends on observation unless able to get *bolometric* luminosity.
   (c) **Insert demonstration of Sun's magnitude between planets and of distance modulus**.

16. Relating to Hubble's Law
   (a) Here's how to measure distance.
   (b) Need to use **standard candles** where you know the intrinsic brightness and **absolute** magnitude.
   (c) Whatever you observe is the **apparent** magnitude.
   (d) This gives you the distance.
   (e) Then you already know how to measure the redshift (that was on the quiz).
   (f) Build up the **cosmological distance ladder** in order to measure H_0.

17. Solar luminosity (recap)
   (a) $L_{SUN} = 3.8 \times 10^{26}\,\text{W}$ (or J/s).
   (b) This is measured as well as predicted by models.
   (c) From this we can measure flux at any distance (at surface it's $6.3 \times 10^7\,\text{J/S/m}^2$.
   (d) This gives you a $T_{surf} = 5800\,\text{K}$ from Stefan-Boltzmann's Law.

(e) The apparent magnitude of the Sun in visible band is -26.74 mag, which is apparently bright.

(f) But the absolute magnitude is 4.83 mag which is not very bright.

18. Concept question: why does the Sun shine? (Attack the misconception.)

    (a) Because gravity compresses gas

    (b) This raises pressure, density, and temperature in the core.

    (c) The radiation is eventually released, which is shining, (unless the star was completely opaque.)

    (d) Metals have a thing to say about how radiation gets out.

19. Hydrostatic Equilibrium

    (a) Gravity pushes in.

    (b) Something resists outwards. That's pressure.

20. Outward pressure

    (a) Pressure is force per unit area and balances F_{grav}.

    (b) The pressure can manifest as gas pressure or radiation pressure, if there's a source of flux.

    (c) The temperature in the core can be due to energy from gravitational contraction.

21. Concept question: how does the Sun continue to shine (for 4.6 Gyr)?

22. Thermal equilibrium

    (a) Sun is losing energy as it shines (due to luminosity).

    (b) Energy loss will decrease pressure, density, temperature in core.

    (c) This decreases resistance to gravity.

    (d) UNLESS energy is replaced and density, pressure, temperature is increased.

23. Nuclear fusion

    (a) Source to **maintain equilibria**, thermal as well as hydrostatic, which keeps the star shining.

(b) Primary reaction in main-sequence Sun is p-p chain, which takes 4 protons and eventually makes 1 He (ionized). Releasing 26.7 MeV of energy per reaction.

(c) Note: this is not the same reaction as in the early Universe, which was 2 p and 2 n coming together.

24. Conditions for Fusion

    (a) Core is hottest part of Sun.

    (b) Technically, overcoming Coulomb barrier between protons is 0.7 MeV, but the average particle has only 1.3 keV in the center. Quantum tunneling permits this reaction to happen.

    (c) $P_{rad} = F/c$ where F is flux, for absorbed radiation. (If reflected, then the pressure is doubled.)

    $$F = 3.5 \times 10^{11}\,\text{atm} \cdot 1\,\text{N/m}^2 \cdot 3 \times 10^8\,\text{km/s} = 1 \times 10^{25}\,\text{J/s/m}^2$$

    (d) 1 Pa = 1 N/m^2 = 9.87×10^{-6} atm (N = kg/m^2/s^2).

    (e) Density of water given as a reference.

    (f) http://zebu.uoregon.edu/~rayfrey/321/lecture5.pdf

25. Stability of hydrostatic equilibrium

    (a) Nuclear fusion *very* sensitive to T_{core}

    (b) Everything will adjust rapidly to compensate for changes in the core.

    (c) Maintains **equilibria**.

    (d) As the Sun evolves *on the main sequence*, the density of the core increases → the radius to decrease → energy increases → temperature increase.

    (e) More energy produced and radiated away. So the Sun becomes more luminous.

26. Stars, beyond the Sun

27. Sun and Stars: comparison of values

    (a) The Sun is in no way special, save perhaps for the fact that it is a single star.

    (b) Though there is the Nemesis theory.

28. Stellar Mass: "I'm the decider" (Bush-ism)

(a) T_{surf}, L, R, t_{age} depend on mass to varying degrees.

(b) As do other properties.

(c) And how they die.

29. Mass-Radius relation

(a) $T_{core} \approx M/R$. Think of this like a piston. The mass doesn't change, but the radius decreases to increase the temperature. The photons or particles hitting the contracting "piston" will reflect with more energy than before, which translates to more heat in the star.

$$P = \frac{N}{R^3}\ k\ T_{core} = \frac{G\ M\ m_a N}{R^4} \rightarrow T_{core} = \frac{G\ M\ m_a}{k\ R}$$

(b) Since T_{core} roughly constant, $R \propto M$ except for very hot stars when $R \propto M^{0.5}$.

(c) **Hydrostatic equilibrium** sets radius of the star once its mass is set. Stars have precisely the radius they need.

(d) http://www.astronomy.ohio-state.edu/~dhw/Intro/lec10.html

30. Stellar temperature

(a) Observe T_{surf} because of Wien's Law.

(b) Physics let's us know that T_{surf} and T_{core} are proportional.

(c) Hydrostatic equilibrium sets the core temperature proportional to M/R.

(d) Core temperature actually fairly constant over whole mass range, because nuclear fusion very sensitive to temperature, so mass scales as radius (as discussed).

(e) Therefore, T_{surf} doesn't change much.

(f) But luminosity can be quite different because it depends on surface area and T_{surf}^4.

31. Spectral classification

(a) The surface temperature will control how the spectrum looks. Namely, the number of lines.

(b) Used to be A–G, based on the hydrogen lines, but his is more correct.

(c) Mnemonics.

(d) 2nd figure: More able to see where H lines are and where molecular lines are.

32. Stellar luminosity classes

    (a) We're discussing the main sequence, Roman numeral five.
    (b) The other classes are "evolved" states.
    (c) You can see the effect of surface area (radius) on luminosity.

33. Stellar structure

    (a) Convection occurs when there is a steep temperature gradient.
    (b) Where there is no convection, a composition gradient is set up.
    (c) Low-mass stars are convective all the way from the core to the surface.
    (d) High-mass stars are convective in their core and not above; this increases the H brought to the core for fusion and prolongs the life. Higher mass stars have larger convection zone, but it never reaches the surface.
    (e) Over time, the high-mass star's convection zone decreases, and a composition gradient is set up.
    (f) Core temperature remarkably constant despite mass. $0.1\,\mathrm{M}_{SUN}$ star has $T_{core} = 4 \times 10^6\,\mathrm{K}$, and $50\,\mathrm{M}_{SUN}$ star has $T_{core} = 40 \times 10^6\,\mathrm{K}$.
    (g) Note: luminosity function of temperature and surface area.

34. Mass-Luminosity relation

    (a) Rate of radiative leakage from stellar interior: $L \propto RT^4 l_{mfp}$
    (b) Opacity in MS stars is $l_{mfp} \propto T^{3.5}/\rho^2$ for low- to medium-mass stars and $l_{mfp} \propto 1/\rho$ for high-mass stars.
    (c) Know $\rho \propto M/R^3$
    (d) From hydrostatic equilibrium $P \propto GM^2/R^4$
    (e) The total pressure can be the gas pressure for all mass stars $P \propto \rho T$ (Ideal Gas Law). But for radiation-pressure dominated high-mass stars $P \propto T^4$.
    (f) From these values, we can prove that for low- to medium-mass stars $L \propto M^{5.5}/R^{0.5}$, for high-mass stars $L \propto M^3$, and for very high-mass stars $L \propto M$.
    (g) http://ngala.as.arizona.edu/dennis/astr250/hw4.pdf

(h) Derivation here (http://personal.tcu.edu/∼pmarcum/courses/p3113/handouts/mlderiv.html)

35. Lifetime

(a) Can consider $t_{age} \propto M/L \approx M/M^{3.5} \approx M^{-2.5}$.

(b) Else, can use Einstein's $E = mc^2$:
$E_* = Lt$
$Lt = (0.0071/4)(M/2)c^2$, assuming half star's mass fused, so 4 protons make He with energy loss 0.71%.
$t = 8.9 \times 10^4 Mc^2/L$
$t \propto Mc^2/M^{3.5} = c^2 M^{-2.5}$

(c) http://zebu.uoregon.edu/∼js/ast122/lectures/lec14.html

36. Stellar Fusion

(a)

(b) CNO cycle is
$^{12}C + ^1H \rightarrow ^{13}N + \gamma$
$^{13}N \rightarrow ^{13}C + e^+ + \nu$ $(\beta - decay)$
$^{13}C + ^1H \rightarrow ^{14}N + \gamma$
$^{14}N + ^1H \rightarrow ^{15}O + \gamma$
$^{15}O \rightarrow ^{15}N + e^+ + \nu$ $(\beta - decay)$
$^{15}N + ^1H \rightarrow ^{12}C + ^4He + \gamma$

(c) CNO cycle requires that C, N, and O exist in the stars. The very early stars were massive and metal-free, so couldn't burn by this process.

(d) **Presentation article**: Population III stars.

37. Stars (recap)

(a) **Mass** determines majority of characteristics like L, R, t_{age}.

(b) Life is about **equilibrium** or balance.

(c) Primarily composed of H, He. How much? About 75% and 25% by mass. The other elements are **metals** and play important part but not really discussed here.

(d) The **main sequence**–which is the main focus of *this lecture*–is when H is fused into He.

38. Synthesizing the relationships between M, F_{grav}, $P_{out} = P_{core}$, T_{core}, T_{surf}, L, F

39. Main sequence Equilibria series
    (a) This is concept map, helps shows ties, because they're not linear.
    (b) Handout blank version for notes. They can use this for tests in the future.
    (c) Step through it.
40. How to plot all this information? (Astronomers' densest plot.
41. Hertzsprung-Russell diagram
    (a) Axes first
    (b) Ask where high-mass and low-mass stars are.
    (c) Point out that I've already started color coating the stars.
    (d) Then go on to a real HRD (just the main sequence).
    (e) Talk about statistics (if there's time).
        i. How many hours do humans spend doing what?
        ii. What if aliens wanted to know?
        iii. Maybe they don't have an 24-hr to spend?
        iv. Like the **shape station** results, HRD has power of statistics.
42. Next: stellar evolution
    (a) Already got a taste from article.

11 Objects in the Universe: Stars II

1. Let's make this a fun, relaxing lecture.
2. Stars (recap)
   (a) Mass determines majority of characteristics (L, R, t_{ageA})
   (b) Life is about equilibrium (balance)
   (c) Primarily composed of H, He and some heavier elements (metals) that play an important part of a star's life, despite being a minority.
   (d) Fuse H into He for majority of life (main sequence)
   (e) Exhaust H and **evolve** and the fate depends on mass.
3. HR diagram and main sequence figure (again)
   (a) Recap that hotter, brighter, bluer is upper left and cooler, redder, dimmer is lower right.
4. Full HRD with all the evolved stars
5. Stellar lives in a nutshell
   (a) Low-mass and long-lived at the bottom
   (b) Some of the lowest mass objects are as old as the Universe.
   (c) High-mass and short-lived at the top
6. Birth of stars
   (a) 10–100 K molecular H_2 clouds are just hanging out in space.
   (b) When an overdensity forms (maybe a shockwave from a nearby supernova), gravity takes over.
   (c) Eventually T, P, ρ increase to the point when H fusion occurs.
   (d) HR figure of the pre-main-sequence (Hayashi) track.
   (e) There's even evolution on the main-sequence as the conditions in a star's core changes (composition).
   (f) Star formation regions are obscured in the visible because of the dense gas and dust. But the infrared is a good probe. See Orion Nebula images.
   (g) Planet (and/or binary star) formation is extension of the collapse. Planetary disk is a flattened pizza dough.

(h) Planets are expected to be rather common. And it seems like planets form around stars with more metals.

(i) Evolution onto main sequences is faster for higher mass stars. (Article said this too.)

(j) Now we skip a long time of the star that is the main sequence.

7. Stars stay on the main sequence longer if they are lower mass. We covered this.

8. The death throes can be dramatic in all cases. Where the star "moves" on the main sequence show how the brightness and color changes.

9. For low-mass stars ($M < M_{SUN}$) the fate will be a red giant and then planetary nebula.

   (a) The Sun will increase in size, increasing its luminosity, while decreasing in temperature, which turns it redder.

   (b) It will eventually have some core He fusion.

   (c) Red giants are mysterious.

   (d) There will be some shell H-burning.

   (e) Greg Laughlin discretionary funding

      i. http://query.nytimes.com/gst/fullpage.html?res=9C00E6D81431F934A25755C0A9679C8B63

      ii. http://www.sptimes.com/News/062501/Floridian/In_a_news_flash__scie.shtml

   (f) As low-mass stars evolve, some become very special variable stars which help set the cosmic distance ladder.

   (g) Electron degeneracy pressure stops collapse at a white dwarf.

   (h) Planetary nebula phase

10. *The Cosmic Perspective* figures were found at http://www.bramboroson.com/astro/apr3.html

12 Objects in the Universe: Galaxies I

1. "The Life Cycle of Galaxies" self- and peer-teach activity
2. Article outline
   (a) Big ideas
   - Classification: seeking underlying formation and evolution scenarios that create each type (*e.g.*, AGN in bulges); visual or parameterized
   - Formation and evolution: hierarchical structure formation, stars then smallest galaxies, then larger, etc; AGN as component in galaxy evolution; environment; equilibrium
   - Feedback: individual stars are important to galaxy evolution: fix cooling catastrophe, angular momentum problem, and missing satellite problem.
   - Dark matter: effects; needed for rotation curves of galaxies
   - Galaxy models: (CDM good for structure formation

   (b) All ideas to cover:
   - $M_{BH} - \sigma$ relation
   - Mass-luminosity relation
   - Interaction versus merger
   - Chaotic versus ordered orbits
   - (Visual) morphological classifications
   - Cycle of gas and dust (so effect of feedback)
   - Nature of simulations (SAMS vs particles vs SPH)

   (c) *Galactic Species*
   i. Morphological classification (visual)
   ii. Ellipticals smooth and round with little gas and dust; chaotic orbits and old; typically brighter than spirals; 10%–20% of "field" but dominate in dense environments
   iii. Spirals may have bar and spheroid (bulge); more likely in the "field"
   iv. Irregulars are outliers, due to interactions or isolated (puzzling), gas rich or gas poor, tend to be dwarfs
   v. Morphology-density relationship

   (d) *Light and Dark*
   i. AGN (brightest are quasars), due to supermassive black holes, and part of *galaxy formation*

ii. Peak of AGN at $z \approx 2$ (1/4 present age) which is peak of star formation in *ellipticals* (?)
iii. CDM, now decoupled from baryons
iv. Structure formation started out as small overdensities in the early Universe

(e) *Sit Back and Relax*

i. Protogalaxy and relaxation (very much like star formation because all depends on hydrostatic equilibrium).
ii. CDM only interact by gravitational field (violent relaxation)
iii. Hierarchical structure formation due to CDM (b/c if dark matter was something else, Universe would look different)

(f) *Take a Spin*

i. Spiral galaxy formation (much like planetary disk formation)
ii. Ellipticals and spiral bulges form from mergers where stars cannot settle into disk (and lack of gas due to efficient star formation during merger).
iii. Evidence of mergers early in the Universe because farthest galaxies disturbed
iv. Since ellipticals and bulges probably from mergers, then supermassive black holes probably from mergers too (since they reside in bulges)
v. Dwarf galaxies are leftovers and very susceptible to small random events

(g) *Some Feedback, Please*

i. First, cooling catastrophe (last section, actually) is that in CDM gas should have cooled efficiently and landed in middle of halos; need energy
ii. Second, CDM fails because disks are too small (angular momentum problem)
iii. Third, missing satellite problem
iv. CDM good for so many things, we stick with it
v. Star formation and feedback seem to be key to fix cooling catastrophe, angular momentum problem, and missing satellite problem.
vi. Hard to simulate because so small but otherwise, large and small scale tied together.

3. Goals:

(a) Learn how to learn (practice synthesizing information, organizing information, and tying new information into old information.)

(b) Synthesize and organize information about article; everything I would just lecture about is in the article, so understand the article, you understand the topic.

(c) Tie in the new information from the article with the pieces you've been presented with during the course.

4. Activity

   (a) Share what we're going to do

   (b) Individual reflection

      i. Gives those who didn't read article chance to catch up.

      ii. List main/*important* points of article

      iii. Aim for the biggest ideas possible.

      iv. Keep side bar of questions

      v. It's not necessary to *understand* a concept to *know* it's an important point (see frequency of it being mentioned, when in article, how many figures, in abstract, etc.)

   (c) Compile group's list of important points and organize

      i. Show how by sentence structure or article structure the main ideas are highlighted

      ii. **Definitions** of new terms, some now, some later

      iii. Ask to hold questions until small-group work

   (d) Small group work

      i. Assign each group a galaxy to figure out:

         - What morphological type is this?
         - How did this form?
         - What does it look like it's doing now? Are different regions of the galaxy doing different things?
         - What can't we see but can bet is going on?
         - What are the contingencies? For example, if this is in an isolated region of space compared to a region with lots of other, close galaxies, what changes about our idea? Or, if this is actually a really small galaxy?
         - Does it have an AGN? How do we know?

- What information presented in class relate to this topic?

ii. Group A given SBc galaxy NGC5334 (student results):
  - Looks similar to SBc ∼M58 on Hubble's "tuning fork" in article
  - Spheroidal clump of stars that look like mini-elliptical galaxies
  - "Barred" = rectangular structure in center
  - If spiral galaxies have a bulge, we infer that NGC5334 has a black hole.
  - Appearance of spiral structure because of the morphology of the spiral arms
  - Outer spiral arms show blue new formations that are hot
  - Star formation in the arms, but older core
  - Spiral arms containing gas and dust only when they're by themselves
  - When in clusters, the ellipticals dominate; when outside clusters, spirals dominate
  - Circular orbit

iii. Group B given E galaxy NGC4636 (student results):
  - Central bulge
  - Older stars based on color, temperature is cooler
  - Very bright center
  - Active Galactic Nucleus
  - Has a black hole in the center
  - Has not had interaction or collision with another galaxy
  - Two competing views on formation of ellipticals

    A. Most stars and bulges formed during a monolithic collapse at early epochs.

    B. Relatively late comers, been produced as a result of merging spiral galaxies.
  - Could of been 2 spiral galaxies that have collided and formed an elliptical
  - No dust and gas (gas has been used up)
  - Could be part of a high-density environment
  - Gas could be used up by the stars, sucked into the black hole, and/or supernova could have knocked it away
  - Dark matter?

iv. Group C given S0/Irr galaxy NGC4753 (student results):

- Elliptical, irregular
- Disheveled... might have had past collision
- Orange... old stars (old galaxy)
- Most uniform “haze”; has big “smudge”
  - Smudge is darker... gas cloud
- Non-symmetrical... recent collision
- “Protoelliptical”
- Black hole, supernovae, or new star formation could get rid of smudge
- Dark matter might look somewhat disheveled as well, just like rest of galaxy

v. Half-way through, group B and C combined to create narrative

(e) Share-out

i. Every group shares and discussion ensues.

5. Main ideas students listed:

(a) Environments: spiral galaxies more alone; ellipticals have more neighbors

(b) Morphological classification: spirals, ellipticals and irregulars; dwarf galaxies; disturbed galaxies

(c) Equilibrium (hydrostatic during formation)

(d) Supermassive black holes, AGN, bulges

(e) Dark matter: cold dark matter

6. Questions students named:

(a) What does it mean to have AGN, black hole, and 10% energy emitted?

(b) What is cold dark matter?

(c) What does “disturbed” mean?

(d) How do we classify?

7. Misconceptions/themes to address:

(a) Hubble tuning fork diagram is *wrong*; originally Hubble though this was an evolutionary sequence.

(b) Old or young stars does not equal old or young galaxy

(c) Major vs minor merger (or generic interaction)

(d) Dark matter just interacts by gravity and can be disturbed but does not necessarily reflect morphology of luminous matter

(e) Idea of spirals in clusters being "anemic" (lack of gas)

(f) Making conditional statements to where conjecture is

(g) Retrieving information from article and processing and applying (especially with the dark matter)

13 Objects in the Universe: Galaxies II

1. Milky Way
   (a) SBc
   (b) 100,000 Ly across
   (c) 12,000 Ly thick in gas, 1,000 Ly thick in stars
   (d) 200 to 400 billion stars but $5.8 \times 10^{11}\ M_{SUN}$
   (e) Oldest star 13.2 Gyr
2. Multi-wavelength Milky-Way
   (a) Radio continuum (408 MHz): electrons in ISM electromagnetic field moving relativistically, also supernovae
   (b) Atomic hydrogen in radio (21-cm, 1.4 GHz): "cold and warm" ISM
   (c) Radio continuum (2.4–2.7 GHz): hot, ionized gas and high-energy electrons in electromagnetic field
   (d) Molecular hydrogen H_2: actually CO J=1–0 transition; cold, dense gas
   (e) Infrared (12, 60 and 100 μm): warm dust; thermal blackbody
   (f) Mid-infrared (6.8–10.8 μm): PAHs (polycyclic-aromatic-hydrocarbons); cold because complex molecule
   (g) Near-infrared (1.25, 2.2, and 3.5 μm): cool giant K stars and not much dust obscuration
   (h) Optical (0.4–0.6 μm): optically thick dust obscuration but also some glowing, low-density gas
   (i) Ultraviolet: blackbody of optical stuff continues
   (j) X-Ray (0.25, 0.75, 1.5 keV): soft X-Rays from hot, shocked gas
   (k) Gamma rays (¿300 MeV): collisions of cosmic rays with hydrogen nuclei in ISM; pulsars
3. Sensitivity and Resolution
   (a) Sensitivity proportional to diameter squared (light bucket)
   (b) Resolution scales with diameter directly: $ang(") = 1.22\lambda/D$
4. Ellipticals can be over $10^{12}\ M_{SUN}$

5. NGC2420 Open Cluster
    (a) CMD has [Fe/H] = -0.44: 3.2 Gyr (solid line);
    (b) http://www.astro.ljmu.ac.uk/research/stellar_population_modelling.shtml
6. 47 Tuc Globular Cluster
    (a) Grundahl, Stetson, and Andersen, A&A 395, 481-497 (2002) "The ages of the globular clusters M71 and 47 Tuc from Strömgren *uvby* photometry"
7. Sagittarius Dwarf Irregular Galaxy
    (a) Layden and Sarajedini,ApJ 119:1760-1792, 2000 April "Photometry of the Globular Cluster M54 and the Sagittarius Dwarf Galaxy: The Age-Metallicity Relation"
8. Flight to the Virgo Cluster
    (a) Milky Way band
    (b) See Orion constellation
    (c) Fly towards sword, towards Orion Nebula
    (d) Past Horsehead Nebula (150 Ly)
    (e) Rosetta Nebula with shell of hot gas from young stars
    (f) Crab Nebula (SN remnant); pulsar blinks
    (g) Leave thin disk of Milky Way
    (h) Look back at Milky Way
    (i) See two Magellanic clouds and other satellites
    (j) Turn towards Andromeda spiral (M31, background) and M33 (foreground); other large objects in our group
    (k) Pass through nebula of hot gas in M33 (2 MLy)
    (l) Background points are galaxies
    (m) Virgo cluster viewed off to the left in background
    (n) Meandering path to close pair M831 and disturbed M82
    (o) Pass M101 (Pinwheel)
    (p) Pass M51 (Whirlpool) and its companion (interaction)
    (q) Wide swing through Ursa Major Cluster

(r) Now move towards Virgo Cluster (50 MLy)
(s) Fly towards central Virgo-A or M87 with its jet from its AGN
(t) http://ifa.hawaii.edu/∼tully/outreach/movie.html

9. SDSS movie
   (a) Part 1: from sun to local galaxies, just before Sloan galaxies kick in
   (b) Part 2: Sloan galaxies with no quasars, zoom out straight to the farthest ones
   (c) (Part 2alternate: doesn't zoom out as much, but rotates)
   (d) (Part 3: follows 2a, rotates the other way)
   (e) Part 4: zoom straight out now, brightening quasars and CMB
   (f) Part 5: CMB spins 360 degrees
   (g) http://astro.uchicago.edu/cosmus/projects/sloanmovie/index1.html

10. Hubble Deep Field
    (a) 1995
    (b) WFPC2
    (c) 10 total DAYS of observing, near the Big Dipper (Ursa Major)
    (d) HST orbits 15 times a day
    (e) (Southern version similar from 1998)
    (f) **Cosmic variance**
    (g) Redshifts $z \lesssim 4.5$
    (h) WFPC2 covers 5.3 arcmin^2 or 4.6 Mpc at $z \approx 3$ or the size of a dime at 75 ft.
    (i) Little finger is 1° at arm's length; moon is 0.5°.
    (j) Size of a dime at 2.3 mi (3.7 km) is 1 arcsec
    (k) http://www.adass.org/adass/proceedings/adass99/O1-01/

11. HST medium-deep Survey
    (a) 5 to 7 GLy ($z \approx 1$)
    (b) http://hubblesite.org/newscenter/archive/releases/cosmology/1994/39/image/a/

12. HST galaxy building blocks (giant star clusters)

(a) 11 Gyr ago
(b) $z \approx 2.5$
(c) http://hubblesite.org/newscenter/archive/releases/1996/29/

13. Hubble Ultra-Deep Field
    (a) 11.3 days with ACS in 2003–2004
    (b) Taken in center of HDF-S
    (c) $z \lesssim 7$, within 1 Gyr after Big Bang, and seeing objects
    (d) 10 arcmin^2 (so bigger than dime at 75 ft)
    (e) Better because longer observation but also better instrument
14. UDF fly-through
    (a) 5,333 galaxy redshifts converted to distances
    (b) http://hubblesite.org/newscenter/archive/releases/2004/28/video/b

14 Future of the Universe I

1. Remind people of assignments
2. Give presentation schedule (several people were allowed to choose because they were on time to the previous class).
3. Clearly state what they are being graded on during presentation.
4. Cover the good, the bad, and the ugly of presentation slides and skills
5. Also secretly convey content but perhaps students cannot absorb all of it.
6. Re-play SDSS fly-through to discuss large-scale structure
7. Show Brandon Allgood's dark-matter halo semi-analytic model simulation to show formation of structure
8. Discuss how one can just trace dark matter halos and still gain a sense of what the Universe looks like
9. Show just a still of a U. Illinois cosmological simulation and talk about how luminous matter traces dark matter
10. Show stills from U. Washington simulation to contrast the growing structure.
11. Talk about cosmic energy budget of 70% dark energy, 25% dark matter, 4% "invisible atoms" and 1% luminous material
12. Discuss what critical density means for future of Universe.
13. Discuss Anthropic principle
    (a) Be clear that Anthropic Principle doesn't mean you can throw up your hands and declare victory.
    (b) It is used to counter arguments of "Oh, your model would only make our observed Universe one in a million times." That's ok, we may be a one-in-a-million Universe, but we're here to realize that.
    (c) The fact that we exist as we are and as we see things places constraints on formation and evolution of Universe.
14. Break
15. Discussion time on "Dark Energy & the Preposterous Universe"

16. Form groups of 2–3 and have discuss: what are main points and what are your questions

17. After 20 minutes, rearrange groups so that new discussions are fostered.(another 15 minutes)

18. Then get everyone together to discuss points.

19. Big ideas class enumerated:

    - If dark energy 70% of Universe, then simulations/models work out.
    - Vacuum energy is model for dark energy
    - If dark energy uniform, then acceleration is constant.
    - We don't know what dark energy is.

20. Questions:

    - What is "invisible" atoms? Are they just not detected yet or can we not see them? Why are they not dark matter? Is this a hokey word to use?
    - What does it mean for dark energy to be uniform? Is it in the room?
    - What is temperature in empty space

15 Final Presentations

1. Black hole detection (astro-ph)

   Q: How do we decide when we've found a stellar-mass black hole?

   A: Binary systems, accretion disks

   Q: How do we distinguish between a black hole and other dense, dark objects (like a neutron star)?

   A: Physics behind mass limit of neutron stars; determining minimum density of M1 in binary systems

   Q: Why do we predict supermassive black holes in active and non-active galactic nuclei?

      A: High-energy radiation rules out thermal processes.

      A: Required mass-to-light conversion.

      A: Jets within 10% of AGN

      A: Infrared measures of central Milky Way stars

2. Supernova

   Q: Why are supernovas important?

   A: When a supernova explodes it releases the chemical elements back into the interstellar medium, enriching space again so more stars can form.

   Q: What is the gas and dust expelled by a supernova?

   A: Supernova remnant.

   Q: True or false: A supernova can radiate as much energy as the sun could emit over its lifetime.

   A: True

3. "The Supernova Origin of Interstellar Dust," E. Dwek, *Science*, 14 July 2006, Vol. 313

   Q: Though interstellar dust only makes up about 1% of the mass within interstellar mediums, why is it still so crucial to the make up and formation of stars?

   A: Because it regulates its thermal energy balance as well as providing material for the formation of planetesimals around main-sequence stars.

   Q: Why do astronomers see interstellar s as inferred?

- A: Because of the interaction with electromagnetic radiation as well as interstellar dust is depleted of various refractory elements from the gas phase within interstellar medium.
- Q: What are two of the observable signatures within interstellar dust after a supernova event when trying to calculate the total amount of dust condensed within the ejecta?
- A: The sudden appearance of a mid-infrared thermal emission component and a concurrent decrease in the ultraviolet-optical light curve of the supernova.

4. "Dark, Perhaps Forever," D. Overbye, *New York Times*, June 3, 2008

   - Q: What is the goal of J-dem, or also known as Joint Dark Energy Mission?
     - a: to return large amounts of data on visible Universe
     - b: to return large amounts of data on invisible Universe
     - c: to refute or propose Einstein's constant
     - d: all of the above
   - A: d
   - Q: True/false: there is a way to measure dark energy
   - A: True
   - Q: Dark energy accounts for ____% of the total mass energy of the Universe.
     - a: 25%
     - b: 73%
     - c: 66%
   - A: b: 73%

5. View from the Center

   - Q: How is it that humans are so central to the Universe given its immense size and composition?
     - A: We (humans) are made of the rarest elements and atoms in the Universe–one hundredth of one percent of all matter to be exact.
     - A: The human size-scale is almost exactly in the middle between the smallest size (Planck length) and the entire visible Universe, the largest thing we can see.
     - A: We live at the midpoint of cosmic time.
     - A: Our solar system is at the mid-point of its life.

- Q: What is the role of dark energy in the Universe?
- A: Dark energy is believed to be the force that causes the Universe to continue to expand, and more importantly so at an exponential role.
- Q: How can cosmology and religion move toward a synthesis?
- A: Both cosmology and religion help is understood our relationship to the larger Universe, and so in effect, help us create meaning. Eventually, our religious must coincide with the Universe that scientists are observing empirically. Otherwise, there will be an existential dissonance. Thus, cosmology and religion will eventually converge at the same point.

6. "Movie Camera to the Stars," L. Marschall, *Discover*, May 13, 2008

- Q: What is the primary aim of LSST (how does it differ from other telescopes)?
- A: LSST is designed to take rapid-fire pictures in order to map out the entire sky very quickly.
- Q: What object could LSST track that might cause the end of the world, and how is it more able to track said object than other devices?
- A: LSST will be more able to track killer asteroids / comets because it can more regularly track their movements.
- Q: What is meant by "synoptic" in "Large Synoptic Survey Telescope"?
- A: "Synoptic" means "Allowing to see the whole". (from article)

7. "Exploding black holes could expose hidden dimensions," K. Than, *New Scientist Space*, 5 February 2008

- Q: Describe Hawking radiation. Would this raise or lower the mass of a micro black hole?
- A: Hawking radiation is a prediction that black holes emit radiation. If an object like a black hole emits radiation than the mass of the object will lower.
- Q: Primordial black holes formed differently than "normal" black holes formed by star collapse. How did primordial black holes form?
- A: In the high temperature high pressure beginning of the universe primordial black holes formed.
- Q: How does a fourth dimension connect with microblack holes?

A: Microblack holes theoretically would have evaporated by now if a fourth dimension did not exist. However if it does exist the gravity of fourth dimension will allow these small microblack holes to exist.

8. "Gauging a Collider's Odds of Creating a Black Hole," D. Overbye, *New York Times*, April 15, 2008

   Q: The LHC (Large Hadron Collider) is said to start smashing protons this summer at CERN. What is the main goal CERN is trying to achieve?

   A: They are trying to grab a piece of the primordial fire, forces and particles that may have existed a trillionth of a second after the big bang.

   Q: Name one major concern that critics have been arguing in impending the startup of the LHC.

      A: Public relations around this matter could be a huge disaster for science.

      A: Calls to question whether the startup will be successful and how much money will be invested in such a large project. Also, if it turns into a disaster, how many lives could be risked as a result.

      A: Safety is a major concern but is debated among critics–some of whom have argued that the project should be followed through and those who argue the opposite.

   Q: When the LHC is activated, it is theorized that the collider will produce the observation to the "missing links" in the standard model of physics. This would be a huge step in what theory? And what does this theory seek to unify (hint: there are three of the four known forces)?

   A: Grand Unified Theory; electromagnetism, strong nuclear force, and weak nuclear force, leaving out gravity.

   Q: The collider must be cooled down to what final operating temperature? What, then is this in degrees Celsius?

   A: 1.9K which is -271.25 degrees Celsius.

9. "Gamma-Ray Burst Afterglows Brighter Than Expected," J. R. Minkel, *Scientific American*, July 8, 2008

   (a) "A Gamma-Ray Burst, in Detail," S. Graham, *Scientific American*, March 20, 2003

   (b) "The Brightest Explosions in the Universe," N. Gehreis, L. Piro, and P. J. T. Leonard, *Scientific American*, November, 2002

(c) "Supernova Signature Seen in Afterglow of Gamma-Ray Burst," S. Graham, *Scientific American*, April 4, 2002

Q: What is a Gamma-Ray Burst? When, if it does take place, in a planet's lifespan does it happen?

A: GRB is a rapid burst of energy (usually gamma-rays) which results from a mass collision or implosion of planets and stars; gamma-ray bursts theoretically occur when a star, post-supernova, collapses into a black hole or when neutron stars collide into each other

Q: How (or at least according to astronomic speculation) are Gamma-Ray Bursts formed?

Q: How are Gamma-Ray Bursts observed?

A: an actual gamma-ray burst, only lasts from five to ten seconds, but because of the lighthouse effect en lieu of debris and dust from supernova an afterglow can be observed for extended periods of time.

Q: How does this tie in with the fate of our own galaxy?

A: if a GRB were to happen within 2000 years of our own galaxy, the ozone layer may be destroyed from the gamma-ray radiation and earth may no longer be able to sustain life

Q: (extra credit) What will kill you faster, i. a Gamma-Ray Burst or ii. a total dictatorial take-over of America by Dick Cheney and Donald Rumsfeld?

A: based on likelihood, the latter probably will; but in the event that both events were simultaneously happening, my money's on the GRB

10. "The End of Cosmology?" L. M. Krauss and R. J. Scherrer, *Scientific American*, February, 2008

Q: 1. What term or idea explains what early astronomers (1908) thought of our galaxy or universe?

  A: Island universe

  A: Our galaxy was thought to be the entire universe

  A: The universe was static and eternal

Q: In billions of years what will the universe look like (list 1 or 2 aspects that will look different)?

  A: Creates fixed "event horizon,"

  A: no matter or radiation will reach us.

  A: Will resemble an inside-out black hole

- A: Matter and radiation will be trapped outside the horizon rather than inside it.
- A: Expanding matter in the universe will be driven outside the event horizon.
- A: Our Local Group of galaxies will collapse into a one huge supercluster of stars.
- A: Other galaxies will disappear into the oblivion beyond the event horizon.
- A: The brightest and biggest stars will have burned up their nuclear fuel
- A: Scientists won't see any galaxies outside of their own when they look in telescopes
- A: Nearby galaxies will have merged with the Milky Way to form one large galaxy,
- A: Galaxies will have gone beyond the event horizon.
- A: Therefore, eventually the cosmic microwave background will become too muted to study and it will be completely unobservable further in the future

Q: True or False: In this article the author explained the likelihood of future astronomers (billions of years from now) never knowing about the Big Bang theory.

A: True

16 Assignments

1. Day 1 (June 23rd): assign to read glossary of terms.
2. Scale U.S. government budget
   (a) AAAS good start
3. Energy history of Universe:
   (a) Energy of Big Bang (http://imagine.gsfc.nasa.gov/docs/ask_astro/answers/980211b.html)
   (b) Energy of H-bomb (http://www.science.uwaterloo.ca/∼cchieh/cact/nuctek/assgnaa.html)
   (c) Energy of H-bomb (http://hypertextbook.com/facts/2000/MuhammadKaleem.shtml)
   (d) Hubble's Law http://astro.wku.edu/astr106/HubbleLaw.html

       But also more background at http://www.astro.washington.edu/labs/clearinghouse/labs/HubbleLawShort/lab.html

       Worksheet (short) http://www.astro.washington.edu/labs/clearinghouse/labs/HubbleLawShort/worksheet.html
   (e) Graph http://www.astro.washington.edu/labs/clearinghouse/labs/HubbleLawShort/images/hubbleplot.jpg
4. Measuring Hubble constant
   (a) http://www.phys.unsw.edu.au/astro/wwwlabs/hdfSize/hdfSize_top.html
5. CMB problem, not only figure out redshift from temperature but also ask about size telescope needed for given resolution or sensitivity.
6. Would like to have problem about galaxies or stars, either measuring density of neutron stars or black holes, or Schwartzchild radius

17 Web Resources

1. Astronomy Notes: http://www.astronomynotes.com/index.html
   Like a textbook on the web.
2. Bad Astronomy: http://www.badastronomy.com/
   Debunking astronomy misconceptions.
3. College-level Astronomy Courses: http://home.eckerd.edu/%7Ehudsonrl/chn/sitescol.html
   List of many many course websites.
4. Stars & Galaxies: A Hypertext Course: http://cosmos.colorado.edu/stem/courses/common/documents/hypertext.html
   Explorable web of information.
5. Reading assignments for astronomy course:
   http://www.public.iastate.edu/∼s2008.astro.250/reading.html
6. Universe 101 by NASA http://map.gsfc.nasa.gov/universe/index.html
7. Dynamical Astronomy JavaLab http://burro.cwru.edu/JavaLab/web/main.html
8. Davison E. Soper class webpages http://zebu.uoregon.edu/∼soper/
9. LISA Reading group where I got the "Life & Death of Stars" *Sky & Telescope* article
   http://gravity.psu.edu//*sim*shane/lisaReadfall05.html
10. Super-string Theory Cosmology website
    http://www.superstringtheory.com/cosmo/index.html
11. Think Space http://library.thinkquest.org/26220/index.shtml
12. Brief History of the End of Everything audio recordings
    http://www.bbc.co.uk/radio4/science/briefhistory.shtml
13. The Universe Adventure http://universeadventure.org/index.html
14. Gene Smith at UCSD Cosmology Tutorial
    http://cass.ucsd.edu/public/tutorial/Cosmology.html
15. Einstein online, about Einstein's relativities
    http://www.einstein-online.info/en/index.html

16. U Washington amazing compendium
http://www.astro.washington.edu/labs/clearinghouse/

18 Glossary of Terms

1. Lexicon: http://nrumiano.free.fr/Elexique.html
2. Common resources for images:
   (a) APOD (Astronomy Picture of the Day)
   (b) Chandra (Chandra Space Telescope)
   (c) HST (Hubble Space Telescope)
   (d) Hubble (Hubble Space Telescope)
   (e) Sloan Digital Sky Survey (SDSS, Sloan)
   (f) Spitzer Space Telescope (Spitzer)
   (g) Wikipedia (Wiki.)
3. Common prefixes (http://physics.nist.gov/cuu/Units/prefixes.html)
   (a) Giga = 10^9 or billion; denoted as G (*e.g.*, 13.7 billion years = 13.7 Gyr).
   (b) Mega = 10^6 or million; denoted as M (*e.g.*, 100 million years = 100 Myr).
   (c) Kilo = 10^3 or thousand; denoted as k (*e.g.*, 11 kiloparsec = 11 kpc).
   (d) Centi = 10^{-2} or one-hundredth; denoted as c (*e.g.*, 3 centimeters = 3 cm)
   (e) Milli = 10^{-3} or one-thousandth; denoted as m (*e.g.*, 5 millimeters = 5 mm)
   (f) Micro = 10^{-6} or one-millionth; denoted as μ and sometimes called *micron* when modifying meters (*e.g.*, 24 micron = 24 μm).
   (g) Nano = 10^{-9} or one-billionth; denoted as n (*e.g.*, 10 nanoseconds = 10 ns).
4. Common measurement units:
   (a) Distance/length:
      i. 1 AU (astronomical unit) = 1.496×10^8 km (average distance between Earth and Sun)
      ii. 1 Å (Ångstrom) = 10 nm = 10^{-10} m
      iii. 1 Ly (light-year) = 9.46×10^{12} km (distance light travels in a year in a vacuum)
      iv. 1 pc (parsec) = 3.09×10^{13} km = 3.26 Ly
      v. 1 R_{SUN} (or $R_\odot$; solar radii) = 695,000 km
      vi. 1 R_{EARTH} (or $R_\oplus$; earth radii) = 6,378 km

vii. z (redshift) $= \dfrac{\lambda_{observed} - \lambda_{rest}}{\lambda_{rest}} = \dfrac{v}{c}$,
where $\lambda_{observed}$ is the observed (measure) wavelength of the light from a source that is moving, λ_{rest} is the laboratory value of the wavelength of the light when the source is not moving, v is the velocity of the object, and c is the speed of light.

(b) Mass:

i. 1 M_{SUN} (or $M_{\odot}$; solar masses) $= 2 \times 10^{30}$ kg
ii. 1 M_{EARTH} (or $M_{\oplus}$; solar masses) $= 5.97 \times 10^{24}$ kg
iii. 1 u = 931.5 MeV/c^2

Particle	Mass		
	(kg)	(u)	(MeV/c^2)
Electron (e^-)	9.109×10^{-31}	5.486×10^{-4}	0.5109991
Proton (p^+)	1.672×10^{-27}	1.0073	938.2723
Neutron (n^0)	1.675×10^{-27}	1.0087	939.5656
Deuterium (D)	3.344×10^{-27}	2.0136	1875.6134
Helium-4 (^{4}He)	6.645×10^{-27}	4.0015	3727.3803

(c) Time:

i. 1 yr (year): not light-year
ii. z (cosmological redshift): the higher the redshift of an object, the farther away the object is in distance, the farther back in time the object is, and the longer the light has traveled in time and distance.

(d) Miscellaneous:

i. c (speed of light) $= 3 \times 10^5$ km/s
ii. X K + 273 K (Kelvin) = $X°$ C, where X is any number
iii. 1 L_{SUN} (or $L_{\odot}$; solar luminosity) $= 3.8 \times 10^{26}$ watts (W), where 1 W = 1 joule/s (or J/s)
iv. 1 J = 1 kg m^2 s^{-2}
v. 1 eV $= 1.602 \times 10^{-19}$ J
vi. 1 Pa = 1 N/m^2 $= 9.87 \times 10^{-6}$ atm (pressure)
vii. 1 N = 1 kg m s^{-2}

5. Useful constants and common symbols:

(a) c (speed of light) $= 3 \times 10^5$ km/s
(b) Wien's Law constant $\kappa = 2.898 \times 10^6$ nm K

(c) Stefan-Boltzmann constant $\sigma = 5.67 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$

(d) Gravitational constant $G = 6.67 \times 10^{-11}\,\mathrm{m^3\ kg^{-1}\ s^{-2}}$

(e) Planck constant $h = 6.626 \times 10^{-34}\,\mathrm{J\,s} = 4.136 \times 10^{-15}\,\mathrm{eV\,s}$

(f) Boltzmann constant $k = 1.381 \times 10^{-23}\,\mathrm{J/K} = 8.617 \times 10^{-5}\,\mathrm{eV/K}$

(g) Hubble constant $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

(h) Solar units

  i. $\mathrm{L_{SUN}}$ (or $\mathrm{L_\odot}$; solar luminosity) $= 3.8 \times 10^{26}$ watts (W), where 1 W = 1 joule/s (or J/s)

  ii. $\mathrm{M_{SUN}}$ (or $\mathrm{M_\odot}$; solar masses) $= 2 \times 10^{30}\,\mathrm{kg}$

  iii. $\mathrm{R_{SUN}}$ (or $\mathrm{R_\odot}$; solar radii) $= 695,000\,\mathrm{km}$

(i) λ (wavelength)

(j) Δ in front of a term indicates a change in the value. For example, ΔE indicates a change in energy.

6. Equations

(a) Wien's Law: $\lambda_{peak} = \kappa\, T^{-1}$
the wavelength of peak emission of a blackbody.

(b) Stefan-Boltzmann Law: $j = F = \sigma\, T^4$,
where j is the "energy flux density" and F is the flux at the surface of the blackbody. Stefan-Boltzmann Law gives you the energy crossing a unit area of the blackbody surface per second.

(c) Luminosity-flux relation: $L = A \cdot F$,
where A is area, in general, and $L = 4\pi\, R^2\, F$ for sphere.

(d) Wavelength-frequency relation $c = \lambda\nu$,
where ν is the frequency in $\mathrm{s^{-1}}$ (or cycles per second) and λ is the wavelength in meters to get c in meters per second.

(e) Photon energy: $E = h\nu = hc/\lambda$

(f) Average kinetic (*i.e.*, motion) energy of particles: $E \approx k\,T$

(g) Mass-energy equivalence: $E = m\,c^2$,
where m is mass and c is the speed of light.

(h) Hubble's Law: $v = H_0\, d$

(i) Gravitational force: $F_{grav} = \dfrac{G\,M\,m}{r^2}$

(j) Pressure: $P = F/A$,
where F is a force and A is the area.

(k) Newton's version of Kepler's 3rd Law: $p^3 = \frac{4\pi^2}{G(M+m)}\, a^3$,
where p is the period of the orbit and a is the average distance between the two masses M and m.

(l) Ideal gas law (gas pressure): $P = n\,k\,T$,
where n is the number of particles per unit volume, k is the Boltzmann constant, and T is temperature.

(m) Radiation pressure: $P = F/c$,
where F is the flux.

(n) Generic magnitude (not necessarily apparent magnitude): $m_1 - m_2 = -2.5 \log_{10}\left(\frac{F_1}{F_2}\right)$,
where object #1 has magnitude m_1 and flux F_1 and object #2 has magnitude m_2 and flux F_2.

(o) Absolute magnitude: $m - M = -5 + 5\log_{10} d$,
where m is the apparent magnitude and M is the absolute (intrinsic) magnitude of the same object and d is the distance from the observer to the object *in parsecs*.

7. Terms and concepts

- Absorption (absorb): process whereby radiation is removed from an impinging radiation source by electrons as they move to higher-energy states in the atoms.
- Abundance: the total number of atoms of an element in an object.
- Angular momentum
- Black hole
- Blackbody (blackbody radiation): idealized model whereby the radiation emitted is strictly due to the object's temperature.
- Brightness: typically an ill-defined term, used loosely to indicate luminosity or flux.
- "Burning": an imprecise term. Astronomers typically mean nuclear fusion and not the chemical sense (whereby oxygen is involved).
- Center for Adaptive Optics (CfAO)
- Center of mass: the point about which two gravitationally-bound masses orbit. The point is closer to the more massive object.
- Clumpy

- Cluster
- Color: a specific wavelength of visible electromagnetic radiation. Typically, when used in reference to astronomical object, it indicates the wavelength at which the object radiates the majority of its visible light.
- Conservation (conserve): a physical quantity cannot be created or destroyed, simply converted.

  (a) Conservation of energy: energy and matter (since $E = m\,c^2$). For example, in the main-sequence stellar core, four particles of (ionized) hydrogen are fused into (ionized) helium in the stellar core. (I specify ionized because there are no electrons attached to the elements; ionized hydrogen is just a proton.) The specific reaction is written thus:

  $$4\,p^4 \rightarrow^4 \mathrm{He} + \Delta E,$$

  where ΔE is the energy *released* by the reaction. (If ΔE had been on the left-hand side of the above reaction, it would have indicated that there was energy *added* to the reaction in order to make it proceed.)

  Applying the mass-energy equivalence (Einstein's equation), total mass-energy at the beginning of the reaction is:

  $$E_{initial} = 4\,m_p\,c^2,$$

  where m_p is the mass of the proton (or ionized hydrogen). The total mass-energy at the end of the reaction is:

  $$E_{final} = m_{He-4}c^2 + \Delta E,$$

  where m_{He-4} is the mass of the (ionized) ^{4}He atom. (The notation, ^{4}He, He-4, and helium-4, indicates that the element is helium, He, and that the total number of protons and neutrons in the nucleus is four.)

  By the law of conservation of energy, $E_{initial} = E_{final}$. With this fact, we can compute the value of the released energy ΔE:

  $$4\,m_p\,c^2 = m_{He-4}c^2 + \Delta E$$

  $$\Delta E = 4\,m_p\,c^2 - m_{He-4}c^2.$$

- Continuum (continuous): radiation produced by particles colliding and emitting energy covering the full range of wavelengths, as in the spectrum of a blackbody source.

- Cosmic microwave background radiation (CMBR): signature of the last-scattering surface after the Big Bang. It's a 3000 K blackbody at $z \approx 1000$. Today ($z = 0$) the CMBR is 2.73 K with its peak wavelength in the microwave range.
- Cosmology: the study of the formation, evolution, and large-scale structure of the Universe.
- Dimensional analysis: generally refers to the process of using units to assess the use of an equation. In this class, it is applied by the use of conversion factors to change units so they cancel and survive appropriately.
- Disk
- Dust: particles of matter larger than a molecule and smaller than a pebble that exist in the Universe and affect the propagation of radiation. Typical terms describing the effects of dust are *reddening*, *extinguishing*, and *scattering*.
- Early-type
- Emission (emit): radiation produced by an electron in an atom moving to a lower-energy state.
- Epoch, era: period of time characterized by some event(s). For example, in the early Universe, there was an inflationary era or epoch.
- Filament (filamentary)
- Flux: the amount of energy released per second per unit area.
- Fusion (nuclear): the process of combining nucleons (protons, neutrons) and/or even nuclei of elements into more tightly bound elements.
- Inquiry: learning science as science is done.
- Intensity: measure of the time-averaged energy flux.
- Late-type
- Light: sloppy term for electromagnetic radiation.
- Line of sight
- Luminosity: the energy released per second.
- Magnitude: astronomical system of measuring the relative flux or luminosity of objects.
- Medium
- Metal: in astronomy, any element heavier than helium.

- Metallicity: the ratio of the number of atoms of metals to the number of hydrogen atoms.
- Nebula (nebulae)
- Nucleus (nuclei): the positively charged core of an atom(s), comprised of protons and neutrons (nucleons) and held together by the strong nuclear force.
- Orbit
- Order of magnitude
- Photon: the particle view of an electromagnetic wave.
- Projection: the two-dimensional rendering of a three-dimensional object.
- Quasar
- (Electromagnetic) radiation: the full range of energies carried by photons, which are also waves.
- Redshift (z): measure of the change in wavelength relative to the original wavelength due to the motion of an object through space (Doppler redshift) or of an object moving with spacetime (cosmological redshift).
- Reflection (reflect): the process of changing a photon's direction without changing its energy (much).
- Revolution
- Rotation
- Scale (verb and noun): (v) to relate physical values to more intuitive values; (n) essentially, the conversion factor that relates the two values.
- Scientific notation: formatting numbers so that there is one non-zero number to the left of the decimal place and any necessary numbers to the right of the decimal place and making up the difference in values by using powers of ten.
- Scientific process: the cyclical method of hypothesizing, experimenting, collaborating, (re-)evaluating and revising (repeat as necessary).
- Singularity
- Spectroscopy: breaking up radiation to measure the flux or luminosity at every wavelength.
- Spectrum (spectra): one-dimensional (*e.g.*, plot flux versus wavelength) or two-dimensional (*e.g.*, rainbow) rendering of flux or luminosity of radiation at all wavelengths.

- Structure: the physical organization of an object (*e.g.*, the interior of the Sun).
- Sub-structure
- z (redshift): cosmological redshift is the increase in the observed wavelength of light compared to the intrinsic wavelength due to the expansion of the Universe.