1 Introduction

1.1 Cosmic Perspective

- What is large? What is small? Consider walking from San Diego to Los Angeles. An example of a scale model is a globe. Perhaps the scale is 1 inch = 1000 miles.

- Solar System.
  What is the solar system? For now, let’s say Sun, planets, moons, asteroids, & comets (no other stars!). (“My Very Excellent Mother Just Served Us Noodles.”)
  The scale is 1:10^10. (In astronomy we use scientific notation for large numbers.) No units are needed because they’re the same on both sides. (A person would be 10^7 miles tall in this model.)
  The relative sizes are easy to show in a book or on a screen, as are the relative distances. [sketches 1 & 2] But showing both the relative sizes and distances in the a single scale model can’t be done in a book or on a screen. Could we walk to α Centauri, 4.4 light years away?

- Milky Way.
  What is the Milky Way? It’s our galaxy, full of stars, dust, & gas. There are more than 10^{11} stars in our galaxy. How much is a hundred billion? (Consider salt in Qualcomm...)
  The scale is 1:10^{19}. Or, 1 mm = 1 light year. (A light year is the distance light travels in one year, roughly equal to 10^{13} km.) Or, atom-size = star-size. In this model, our Milky Way would be the size of a football field – with the Sun at about the 20 yd. line.

- Alternate Milky Way model.
  If the ⊙ is a grain of NaCl, the next grain is 7 miles away. This model is useful when visualizing galaxy collisions.

- Universe.
  The universe is everything that exists. There are more than 10^{11} galaxies in the universe. → 10^{22} stars. How much is 10^{22}? (Consider grains of sand...)

- In astronomy, it’s not acceptable to confuse the solar system, the galaxy, and the universe.

- Time.
  Now the scale model is 1 year = age of universe. (The age of the universe is about 13.8 billion years.)
  January 1: big bang
  (the beginning of space, time, matter, energy, force, ...)
  February: Milky Way forms
  September 3: Earth forms
  September 22: earliest life on Earth
  December 26: rise of dinosaurs
  December 30: extinction of dinosaurs
  Dec. 31, 9 p.m.: earliest human ancestors

1 Model sizes in mm for the Sun and 8 planets are as follows: 139, .5, 1.2, 1.3, 1.7 14.3, 12.0, 5.2, and 4.8. Model distances in m from the Sun to the 8 planets are as follows: 6, 11, 15, 23, 78, 143, 287, and 450.

2 htwins.net; The Known Universe by AMNH; cosmic eye; atlasoftheuniverse.com; Cosmic Voyage.

2. Motions.
  How does Earth move? Like a top on a record player on a merry-go-round.

<table>
<thead>
<tr>
<th>motion</th>
<th>speed</th>
<th>period</th>
</tr>
</thead>
<tbody>
<tr>
<td>rotation</td>
<td>600 mph</td>
<td>1 day</td>
</tr>
<tr>
<td>precession</td>
<td></td>
<td>26,000 yrs</td>
</tr>
<tr>
<td>revolution</td>
<td>60,000 mph</td>
<td>1 year</td>
</tr>
<tr>
<td>galactic orbit w/ “bounce”</td>
<td>600,000 mph</td>
<td>230 × 10^6 yrs</td>
</tr>
<tr>
<td>Milky Way toward Andromeda</td>
<td>180,000 mph</td>
<td>v = H0r</td>
</tr>
</tbody>
</table>

3. Reading.
   - TCPF2: Chapter 1, Sections 1 - 2.

4. Homework.
   1. (3 points) List the eight planets in order of increasing distance from the Sun.
   2. (5 points) Planet A is roughly how many times further from the Sun than the Earth is? (Planet A can be any of the seven other planets.)
   3. (8 points) Consider our scale model of the solar system. How far would we have to walk to reach the ⊙'s nearest neighbor, α Centauri? (To answer this question, you must set up the appropriate ratio and solve for the correct quantity.)
   4. (8 points) Consider our two visualized models of our galaxy, the Milky Way. In the first, stars were the size of an atom, α Centauri was 4.4 millimeters from the ⊙, and the galaxy was 100 yards across. In the second, stars were the size of a grain of salt, α Centauri was 7 miles from the ⊙, and our galaxy would be how far across? (To answer this question, you must set up the appropriate ratio and solve for the correct quantity.)
   5. (3 points) In Chapter 20 of Part 2 of Bridge of Birds, Barry Hughart writes the following. “The Bamboo Dragonfly flew steadily on, and flames and smoke spurted out behind us as we drifted gently across the deep purple sky of China; a tiny spark that flicked beneath the glow of a million billion trillion stars.” Is this statement correct or not? If incorrect, how would you correct it? Justify your answers.
   6. (2 points) Briefly explain the difference between rotation and revolution.

1.2 Nature of Science

- Science doesn’t address the “Truth”.

If a statement can be proven, then it can be true.

- Karl Popper – “A theory can never be proven, only disproven.” To prove a theory, one must prove that it can’t be disproven; it must be shown that no experiment can disprove the theory. One would have to perform all possible experiments and show that none of them disprove the theory; this is impossible.
– R. Descartes? What can we be absolutely sure of? Might we be dreaming? He says cogito ergo sum, and that we can be sure of it. His argument appeals to our intuition and common sense, but these cannot be relied upon in these matters. (Consider “eivocae”...)  

• Science seeks to describe what we observe, to find patterns, and to make subsequent predictions. (Consider learning gravity...)  

• When evidence contradicts a theory, the theory must be changed or dismissed in favor of a new theory. (Consider a helium balloon...)  

• Science seeks to explain these patterns with the simplest answer (like Ockham’s Razor). What does simple mean and what is a simple theory? To answer this, we must consider the number of initial conditions needed for the theory to happen (like the ingredients in a recipe) and the number of characteristics or parts of the theory (like the steps in a recipe).

– Consider a statement that describes a piece of chalk. How many statements are necessary to describe the chalk completely and exactly? One for the velocity and position of every electron, proton, neutron, etc. We see that even a piece of chalk is far from simple. (Simple: photon(1), black hole(3).)  

– Consider an example in which science must choose, based on simplicity, between two theories. (Neither can be proven; neither can be disproven.) A) The universe was created 5 minutes ago with all of our memories in tact – far from simple. B) The big bang theory – simple compared to A.  

• Further lines of thought include the following.  

“Absence of evidence isn’t evidence of absence.”  

“What cannot be settled by experiment is not worth debating.”  

Benjamin Franklin was once asked, “What is the use of pure research?” He replied, “What is the use of a newborn baby?” Consider the example of knot theory and its intersection with virology. This has implications for voting today.  

• This is a science course. We will discuss what is observed: the clues. We will discuss the laws of nature: the rules of the game – more clues. We will put all the clues together to solve the mystery: doing science. 

Most scientists can control their experiments, but astronomers are observers without such control. Observation is not experimentation. 

• Reading.  

– TCPF2: Chapter 2, Section 1.

1. (8 points) Science seeks to describe what is observed, to find patterns in those observations, and to make predictions based on those patterns. And when observation produces evidence contrary to our theory, we throw away the theory and create a new one. As we discussed in lecture, you all did all 4 of these acts as infants when you learned about gravity and then helium balloons. Discuss another example in which you have naturally behaved as a scientist – include all 4 parts.  

2. (5 points) Given 2 theories which explain some phenomenon, and neither theory can be disproven, Ockham’s Razor helps the scientist choose between them. This is how we chose the big bang universe over the 5 minute old universe during lecture. Discuss an example in which you have applied Ockham’s Razor. How is “simplicity” relevant to your example?

2 Basic Observations & Mechanics

2.1 Sky Coordinates

• Altitude – Azimuth (horizon system). If you were in the middle of the ocean, with no land in sight, you would see the horizon as the circle around you where the sky meets the sea. Altitude is height, ranging from 0° to 90°, measured upward from the horizon. Azimuth tells direction on the horizon, ranging from 0° to ~ 360°, measured eastward from north. This system depends on the location of the observer. [sketch 3]  

• Right Ascension – Declination (equatorial system). R.A. is much like longitude. Dec. is much like latitude. This system does not depend on the location of the observer. [sketch 4]  

• Celestial Sphere. [sketches 5, 6, & 7] To draw: CS, ⊕, hor, Z, NCP (alt. of NCP = lat. of obs.), SCP, CE.

• Reading.  

– TCPF2: Chapter 2, Section 1.

• Homework.

1. (2 points) The Earth is round and so requires a round coordinate system to determine locations (e.g., latitude & longitude). The sky is also round; what coordinate systems do we use for the sky?  

2. (6 points) A star in the sky has (alt, az) coordinates of (40°, 187°). (a) Is the star rising or setting? (b) If azimuth were measured northward from east (instead of the usual eastward from north), what would be the (alt, az) coordinates of the star? Justify your answers.  

3. (5 points) Draw the celestial sphere appropriate to an observer located at 50° N latitude.  

4. (5 points) Draw the celestial sphere appropriate to an observer located at 30° S latitude.

2.2 Earth’s Rotation

• Foucault’s Pendulum is a good idea for demonstration. (Consider the view from above the NP...) [sketch 8]
2.3 Precession

- The $\oplus$ precesses like a top, once every $\sim 26,000$ years. [sketch 9] This has implications for horoscopes...

Sagittarius: Dec 18 - Jan 19
Capricorn: Jan 20 - Feb 15
Aquarius: Feb 16 - Mar 11
Pisces: Mar 12 - Apr 18
Aries: Apr 19 - May 14
Taurus: May 15 - Jun 21
Gemini: Jun 22 - Jul 20
Cancer: Jul 21 - Aug 10
Leo: Aug 11 - Sep 16
Virgo: Sep 17 - Oct 31
Libra: Nov 01 - Nov 22
Scorpius: Nov 23 - Nov 29
Ophiuchus: Nov 30 - Dec 17

Homework.

1. (3 points) In 2700 B.C., the Egyptians saw a different north star (Thuban in Draco) than we see today (Polaris in Ursa Minor). Why?

2. (8 points) (a) If all thirteen zodiacal constellations were the same size on the sky, how many years would it take before everyone’s birth sign had shifted to the adjacent sign? (b) Under the same circumstances, how many years would it take before half of the population had their birth signs shifted to the sign just past the adjacent sign? Justify your answers.

2.4 Appearance of Stars

- Consider how the visible constellations change with the seasons.

- Why do the stars vary in brightness? First is distance; compare a near candle flame to a far one. Second is size; compare a candle flame to a burning building. Third is “intrinsic brightness”; compare a candle flame to a welder’s torch flame.

- Why do stars vary in color? The reason is surface temperature. Blue is hotter; red is not as hot. Consider Orion. [sketch 10]

2.5 Lunar Phases

- There are eight phases of the Moon: new, waxing crescent, first quarter, waxing gibbous, full, waning gibbous, third quarter, and waning crescent. [sketch 11]

- These phases are the result of the changing position of the Moon relative to the Earth and the Sun. [sketch 12]

- From the Earth, we always see the same side of Moon because the Moon is tidally locked with the Earth: $P(\text{rot}) = P(\text{rev})$.

- Rise & set times for the Moon depend on the phase. One may estimate the time of day or night by observing the Moon’s position and phase. (Consider several examples...) [sketches 13, 14, & 15]

To estimate time: draw Earth, direction to Sun, Moon in its orbit, line distinguishing observers able to see the Moon, label one or more relevant times, and box the actual time.

- Earthshine allows us to faintly see the dark side of the Moon; the light from the Sun reflects from the Earth to the Moon and back to the Earth. [sketch 16]

- Reading.
  

Homework.

1. (3 points) In Chapter 4 of Book II of The Fellowship of the Ring, J. R. R. Tolkien writes the following. “The night was old, and westward the waning moon was setting, gleaming fitfully through the breaking clouds.” Is this statement correct or not? If incorrect, how would you correct it? Justify your answers.

2. (5 points) From Coronado, you see a waxing crescent moon just above the Pacific Ocean. What time is it? Why?

3. (9 points, not Astr 120) If you are in Pacific Beach at night, and you see a crescent moon with an altitude of $10^\circ$ and an azimuth of $270^\circ$, which crescent moon do you see and what time must it be? (Please draw diagrams with your answer.)

2.6 Eclipses

- Two types of eclipses are solar and lunar. [sketches 17 & 18]

What are the phases of the Moon during these two types?

- Why aren’t there eclipses every time the Moon orbits? (Consider top view and side view...) [sketch 19] The Moon’s orbital plane is tilted at $5^\circ$ with respect to the ecliptic (a.k.a. Earth’s orbital plane). The line of nodes is the intersection of the ecliptic with the Moon’s orbital plane. When the l.o.n. connects the Earth, Moon, & Sun, eclipses are possible.

- Why don’t eclipses happen every 6 months? Orbits aren’t circular.

- Reading.
  

Homework.

1. (5 points) If the Moon’s orbit were perpendicular to the ecliptic, would eclipses be possible? What would be the most common phase of the Moon? Why?

2.7 Retrograde Motion

- A planet is a “wanderer”; Mercury, Venus, Mars, Jupiter, and Saturn were known to the ancients. [sketch 20]

- Planets normally go from W to E, but sometimes they go E to W. How could this happen? Epicycles? (Is the map backward?) [sketch 21]

\footnote{WSS 100 1-1 (10')}
Imagine passing a slow truck while on the freeway. Consider three views: right windshield, passenger window, & right rear window. The same three views will happen if you’re still while the truck travels in reverse.

Retrograde motion is an apparent backward motion. We on the ☉ pass a slower planet. [sketch 22]

• 2.8 Kepler’s Laws of Planetary Motion
• 2.9 Newton’s Laws of Motion

First. The law of ellipses: a planet orbits the ☉ in an ellipse with the ☉ at one focus. [sketch 23]

What exactly is an ellipse? (Consider 2 nails & string.) [sketch 24]

Second. The law of equal areas: a “planet-Sun line” sweeps out equal areas in equal times. [sketch 25]

Third. The harmonic law: \( P^2 = a^3 \)

Here, \( P \) is the orbital period and \( a \) is the semi-major axis, which is half of the major axis of the ellipse. The unit of \( P \) must be the year and the unit of \( a \) must be the astronomical unit (a.k.a. AU), which is the average distance between the Sun and the Earth. Consider Jupiter (5.2, 11.8) or Saturn (9.5, 29.5).

Kepler was the first to be able to create a scale model of the solar system. [sketch 26]

2.10 Newton’s Universal Law of Gravitation

\[ F = \frac{GMm}{d^2} \]

Here, \( F \) is the gravitational force between two masses, \( G \) is the gravitational constant (a.k.a. Newton’s constant), \( M \) & \( m \) are the masses, and \( d \) is the distance between the centers of the two masses. This is an “inverse-square law”; consider examples including weight.

• 3. Light

3.1 Electromagnetic Radiation (a.k.a. Light)

Why is light so important to astronomers? Almost everything we know about the universe comes to us in the encrypted form of light.

White light (for example, sunlight) is actually a sum of colors. The speed of light is \( c \approx 300,000 \text{ km/s} \). This is like going around the ☉ 7 times in one second.

Light is a wave. (Consider a sine wave, not a breaking wave.) [sketch 28] Wavelength is the distance from one crest to the next. Amplitude is the height of the wave; this is related to the wave’s power. Frequency is the number of crests passing by each second. [sketch 29] Generally, \( c = \omega f \).

What is the physical difference between red light and blue light? Consider spectral bands: radio, microwave, infrared, visible, ultraviolet, x-ray, and γ-ray.

Consider the electric and magnetic waves. [sketch 30]

Light is also a particle\(^8\) it’s called a photon.

\(^8\) Actually \( \vec{F} = \frac{d\vec{p}}{dt} \).

\(^7\) Newton found Kepler’s third is actually \( (P/2\pi)^2 = a^3/[G(M + m)] \).

\(^9\) WSS 180 6-1 (15’), WU 100 3-1, 3-2 (25’). We may compare interference and diffraction with the photoelectric effect and the behavior of CCD’s.
• The Duality of Light: Light is a particle and a wave and neither! This is not intuitive – we don’t grow up with this kind of thing as part of our daily reality. So we find that the universe is a strange, exotic, wonderful place. And we learn that things can exist even if they don’t fit our common sense and intuition.\(^\text{11}\)

• Reading.
  – TCPF2: Chapter 5, Section 1, page 80.

3.2 Observing Instruments & Techniques

• Two types of optical telescopes are the reflector (uses a mirror) and the refractor (uses a lens). [sketches 31 & 32]

• Interferometry is used to improve angular resolution, for which smaller is better. (ang. res. \(\sim w/D\)) Consider headlights at night up close or far away. [sketches 33 & 34]

• CCD’s revolutionized astronomy because now we can add images/exposures together without limit. This allows us to see fainter, and therefore farther, objects. Consider the “Hubble deep field”.\(^\text{12}\)

• Why have a space telescope? Light pollution happens when city lights reflect back down from our atmosphere. [sketch 35] Scintillation (“twinkling”) includes image flickering and jumping around. [sketch 36]

• Reading.
  – TCPF2: Chapter 3, Section 2, page 43.

• Homework.
  1. (3 points) If a reflector and a refractor are the same length, inside which telescope does light have a longer path? Justify your answer.

3.3 Temperature

• What is it? What is the physical difference between hot water and cold water? Temperature is the measurement of the speed of the particles (e.g., atoms, molecules).

• Consider scales and units. \(^\circ\) F, \(^\circ\) C, K.

\[
\begin{array}{c|c|c}
\text{scale} & \text{freeze} & \text{boil} \\
\hline
\(^\circ\) F & 32 & 212 \\
\(^\circ\) C & 0 & 100 \\
K & 273 & 373 \\
\hline
\end{array}
\]

How cold can something get? In accordance with our definition, it’s when the motion of atoms is as slow as possible. This is “absolute zero”; this is 0 Kelvins.\(^\text{13}\)

11 All these years this amazing object, light, has been all around you; did you ever stop to consider its true nature?
12 WU 100 4-3 (9’)

13 The curves are described by the function

\[
B(w) = \frac{2\hbar c^2}{w^5} e^{hc/wkT} - 1.
\]

\(^\text{14}\)20000 K peaks in the UV; 3000 K peaks in the IR.
\(^\text{15}\)WU 100 4-1, 4-2 (21’)

16 Anyone interested in how the eye perceives colors, or why most stars appear white, should investigate the chromaticity diagram.

• Reading.

3.4 Thermal Radiation

• Also known as black body radiation or incandescence.

• Hot objects glow. There are many familiar examples: a glowing hot solid like an iron poker or an electric stove coil, a glowing hot liquid like lava, or a glowing hot gas like our Sun or any other star. (There is no fire on or in the Sun or stars.)

• Why is it called a “black body”? An object that is perfectly black is a perfect absorber & emitter of e.-m. radiation. (Consider what you might wear on a hot day in direct sun. Or in the shade.)

• Black body curves help us understand the Sun and stars\(^\text{13}\). In astronomy, we’re usually concerned with how stars look through our telescopes on the surface of the Earth. Thus, when we consider black body curves for stars, we’re usually interested in starlight after it’s passed through the Earth’s atmosphere. Consider a graph of wavelength vs. intensity – with peaks for 8000 K (blue), 6000 K (yellow), 4000 K (red)\(^\text{14}\). These curves show peaks for radiation influenced by the air in our atmosphere. [sketch 37]

Three rules go along with the curves: hotter is brighter, hotter peaks at shorter wavelength, and hotter is brighter at all \(w’s\).\(^\text{15}\)

Also consider the conventional use of the words “blue” & “red” in astrophysics. By “blue” we mean short wavelength, and by “red” we mean long wavelength. So the second rule can also be stated as “hotter is bluer”.

• At the Earth’s surface, the Sun appears yellow. (Consider the evolution of cones and rods?) Arcturus appears orange; Vega appears blue.\(^\text{16}\)

• Reading.
  – TCPF2: Chapter 5, Section 1, page 80.

• Homework.
  1. (5 points) When considering blackbody radiation, we can safely say that a blue object emits more red light than a red object of the same size. Explain this concept by drawing two blackbody curves on the same graph and labeling all relevant items, including axes.
3.5 Scattering

- What is it? Photons bounce off of tiny particles such as atoms, molecules, microscopic dust. [sketch 38]

Why does blue scatter more than red? It’s related to $1/w^4$.
Consider ratios. [sketch 39]

- Why is the sky blue?
Visualize a blue photon arriving from $\odot$ and bouncing around until it reaches your eyes. You say, “I see blue in that direction.” With all the blue photons, you see blue from all directions and say, “The sky is blue.” [sketch 40]

Consider photons at sunset [sketch 41]

- Why isn’t the sky purple? Consider the BB spectrum of the $\odot$ and the eye’s sensitivity. [sketches 42 & 43]

What color do things look in the moonlight?

- Homework.

1. (5 points) What would be the color of the sky at noon if scattering were related to $w^4$? What would be the color of the setting sun in this case? Justify your answers.

3.6 Exam I

- The following gives the instructions found on the first page of the exam.

  - This is a 50 minute, closed-book, closed-note exam. You may not have enough time to finish if you don’t pace yourself. There are XX fill-in-the-blank questions, worth one point each. The answers of which are to be legibly written on your scantron form, 886-E.
  
  - At the top of this exam and on your scantron form, please write your name. Both the exam and the scantron form must be turned in. If you forget, you will receive a zero grade.
  
  - For each numbered blank, choose the most appropriate answer from the alphabetized list at the bottom of the page. If none are appropriate, choose “de. none of the above”. For each page, use only the answers at the bottom of that page. Some of the answers may be used more than once; some of the answers might not be used at all.
  
  - An answer such as “ab” means to fill in both “a” and “b” for the same blank.
  
  - The scantron boxes don’t need to be completely filled in; a single, heavy, dark line should suffice.

- If you need to erase your marks, do so very thoroughly. If the scantron grading machine detects marks that are not thoroughly erased, you will be marked off for an incorrect answer, and no scoring adjustments will be made later.

- If you are asked to fill in blanks in alphabetical order, alphabetize the answers that fill in the blank, not the letters that fill in the scantron boxes.

3.7 The Classical Atom

- “Classical” implies an older, less accurate, but simpler idea. Consider a simple atom: nucleus and electron. [sketch 44]

The atomic number tells us the element and equals the # of protons in the nucleus.

The atomic weight tells us the isotope and equals the # of nucleons in the nucleus. (A nucleon is a proton or a neutron.) The atomic charge tells us the ion and equals the # of protons in the nucleus minus the # of electrons in the atom.

- Consider examples. How many protons, neutrons, and electrons are in each? $^1\text{H}, \ ^2\text{H}, \ ^4\text{He}, \ ^3\text{He}^+, \ ^3\text{He}^−, \ ^8\text{Li}, \ ^{60}\text{Fe}^{+++}$ $p^+: \ a.n.$ $n: \ a.w. - \ a.n.$ $e^−: \ a.n. - \ a.c.$

- Homework.

1. (5 points) Consider an atom represented by $^9\text{X}^2$. That is, some element X; its atomic number is x; its atomic weight is y and its atomic charge is z. Answer the following three questions in terms of x, y, & z, and justify your answers. How many protons does $^9\text{X}^2$ have? How many neutrons does $^9\text{X}^2$ have? How many electrons does $^9\text{X}^2$ have?

3.8 Quanta, Absorption, & Emission

- Consider the ground state and an excited state. Ground state means the $e^-$ has the minimum possible energy, and excited state means $e^−$ has more than the minimum possible energy. There are many levels (a.k.a. states, orbitals) available to an $e^−$ in an atom. A higher level for an $e^−$ means it has more energy. [sketch 45]

Only certain levels are allowed for the $e^-$; anything in between is forbidden. [sketch 46] This is the Bohr model of the atom.

The atom can only have specific quantities of E. We say “energy is quantized”. What does this imply? This is different from the way things work in our everyday world. Imagine a car accelerating from 50 mph to 60 mph. Can the car go from 50 to 60 without at some point having every speed in between? But jumping this way is exactly what electrons do. If cars behaved like electrons, they could instantaneously leap from 50 mph to 60 mph. When electrons jump from one level to the next, they never have the energy in between; they never even occupy the space in between the levels. They make a “quantum leap”. [previous sketch] (Imagine if you have no money and I then give you a $50 bill. Did you at any time have $20?)
• What makes an electron jump up from one level to the next? The atom absorbs energy. What kind of energy? Light (photons). When an atom absorbs a photon, the $e^-$ jumps up to a higher level; this is absorption. [sketch 47]

\[ E = hf; \]  
\[ E \] is energy of the photon, \( f \) is frequency, and \( h \) is a constant (a number, sort of like \( G \) in gravity, but even smaller). So we see a blue photon has more \( E \) than a red photon.

Since only specific levels are allowed, only specific colors can be absorbed by an atom. That is, the photon has to have just the right \( E \) (which determines \( w \) and \( f \)) in order to be absorbed and make the \( e^- \) jump from one level to exactly another; if the photon has too much or too little, then it will pass right through the atom. There must be a perfect match.

Absorption is basically photon in, $e^-$ up.

• Electrons, when left alone, seek the ground state. This is because the ground state has the lowest energy. This is much like how a ball, left alone on a hill, will roll to the lowest point. This is because the lowest point has the lowest energy.

\[ E \text{mission} \] of a photon occurs when an electron jumps to a lower level. This is the opposite of absorption. [sketch 48]

Since only specific levels are allowed, only specific colors can be emitted by an atom.

Emission is basically $e^-$ down, photon out.

• Consider the example of phosphorescence, which is delayed emission (glow-in-the-dark), involving a metastable state. [sketch 49]

Reading.

– TCPF2: Chapter 9, Section 2, page 152.

• Homework.

1. (2 points) Please briefly explain the difference between a photon and a proton.

3.9 Spectral Lines

• Consider a blackbody, a H cloud, 3 prisms, 3 spectra, and 3 graphs (continuous, absorption, emission). [sketch 50]

A \textit{continuous spectrum} is a blend – no gaps between the colors. [sketch 51]

Light tries to pass through the H cloud; does all of it make it through? No. Why not? Because some of the colors had just the right \( E \) (which determines \( w \) and \( f \)) to be absorbed by the H atoms in the cloud and make them excited. So, particular colors will be missing, but the rest will pass right through – hence, a spectrum with a few dark lines. This is an absorption line spectrum.

Imagine a day when you can see the Sun through the thin clouds above you. Not all of the light makes it through.

Now look at the cloud itself. What will the spectrum look like? A few bright lines. In fact, exactly the colors missing in the absorption spectrum will be found. This is because the excited H atoms proceed to de-excite and emit photons that have the same energies that were absorbed. This is an emission line spectrum.

• Every element, isotope, ion, molecule, etc. has its own set of energy levels. Therefore, each has its own set of colors it can absorb and emit. Therefore, each has a unique set of spectral lines.

• This means we can tell what something is made of by looking at its spectrum. This is spectral analysis. This lines, in general, are called spectral lines.

For example, if a star’s spectrum shows a set of lines unique to H, then we know that the star’s atmosphere contains H. Spectral analysis is probably the most powerful tool of observational astrophysics.

• Consider colors: thermal radiation, scattering, fluorescence, refraction, thin-film interference, diffraction, and so on. In addition to physics, we must also consider physiology and psychology.

Reading.

– TCPF2: Chapter 8, Section 1, page 132.

• Homework.

1. (5 points) Please explain how the sum of an emission spectrum plus an absorption spectrum can equal a continuous spectrum. (Hint: quantized energy)

2. (6 points) Consider the diagram with the prisms in the section Spectral Lines. Can one be sure that the emission spectrum is really an emission spectrum? Or can this spectrum arise from scattering? Consider if it’s possible that the atoms in the cloud scatter only the three colors (red, cyan, violet) in the spectrum by comparing their graphs of brightness vs. wavelength. Justify your answer.

3.10 Ionization, Recombination, & Cascade

• \textit{Ionization} is the process of creating an ion. Most commonly, a neutral atom loses an $e^-$. How can an atom lose an $e^-$? If the photon it absorbs has enough \( E \) to send the $e^-$ past level \( \infty \). Note that level \( \infty \) has finite \( E \) and a finite distance from the nucleus. How?[16]

Consider stepping half way to the wall over and over. How many steps to reach the wall? So we see that it is possible to have an infinite number of steps in a finite distance. This idea applies to the $e^-$ as it jumps up from one level to the next. [sketch 53]

Ionization is basically photon in, $e^-$ out. [sketch 54] The result is 1 ion & 1 free $e^-$. \[ \text{Ionization} \]

• \textit{Recombination} is the opposite of ionization. It is basically $e^-$ in, photon out. [sketch 55]

[16WU 100 2-2 (9')]

[19Recall Zeno’s Paradox, a.k.a. Achilles & the Hare. Achilles runs 10 times faster than the rabbit, but the rabbit has a 10 m head start. [sketch 52] How many decreasing steps are needed for Achilles to catch the hare? "Infinite number." So it seems Achilles will never catch the hare. However, in another second, when Achilles has run the 2nd 10 m stretch, the hare has only run another 1 m. Obviously, Achilles overtakes the hare. This is the paradox. Two logical lines of thought lead to different answers. The Greeks knew Achilles caught the hare, but they couldn’t reconcile this with the series of numbers. It wasn’t until Isaac Newton, who invented calculus, that the paradox was resolved. Calculus tells us that the infinitesimal is valid and real and significant.
3.11 Collisional vs. Radiative Processes

- So far, we have discussed radiative excitation and radiative ionization. Thus called because the energy required to make the e\(^{-}\) jump was supplied by radiation (that is, electromagnetic radiation, which is light – or photons).

- Energy can also be supplied by a collision between 2 atoms. For example, consider a collision between 2 cars. Energy is needed to bend the metal, to do that work. Where does the E come from? From the velocity of the cars.

So, energy can come from the velocity of the particles. The result is collisional excitation or collisional ionization. [sketches 57 & 58]

- There is also collisional de-excitation. [sketch 59]

- Consider the everyday phenomenon of radiative excitation followed immediately by collisional de-excitation.

- Homework.

  1. (5 points) Almost every day, all around you, you witness radiative excitation followed immediately by collisional de-excitation. What is this commonly called? Justify your answer.

3.12 Example: Shooting Stars

- Consider the actual size of a typical shooting star. [sketch 60] So we see that they're not stars at all.

- The \(\odot\), in its orbit (~60,000 m.p.h), runs into little rocks floating around the solar system. The rock enters our atmosphere at that speed. Friction between the rock and the air heats the air and the rock. (Consider rubbing your hands together at 60,000 m.p.h!)

Remember that high temperature means fast particles. So collisional ionization and collisional excitation occur, immediately followed by recombination, cascade, and de-excitation – all of which produce photons. The result is that the path of the rock glows momentarily; we see a shooting star (a.k.a. meteor) [20]

- There are meteor showers. For example, the Perseids are around August 11 every year.

Consider that a comet (sort of a mountain-sized dirty snowball) will sublime as it approaches the Sun. [sketch 61] (Notice the direction of the tail.) So we see that comets litter the solar system with debris. And we see why showers occur annually.

3.13 Magnetic Fields

- The abbreviation used is \(\vec{B}\).

How shall we represent something invisible? With \(\vec{B}\) lines. [sketch 62]

Consider a sketch of a river showing a “velocity field” of water flows. [sketch 63] What do the arrows mean? It’s the same when drawing magnetic fields; they’re not meant to exist only where the lines have been drawn.

- Consider \(\vec{B}\) for a bar magnet. [sketch 64] The lines represent the shape of the force field and the “polarity” of the force [21] [demonstration]

- What happens if we break a magnet in half? What about magnetic splinters, atoms, and subatomic particles? [sketch 65]

- Charged particles interact with \(\vec{B}\)’s. They can run along them, but they can’t freely cross them. [sketch 66]

3.14 Example: Aurora Borealis

- Translates from Latin as “Northern Lights”.

- Recall how charged particles interact with \(\vec{B}\)’s.

- Consider the solar wind, which is the collection of charged particles coming from the Sun. The Sun is sort of boiling and giving off its own version of steam.

- The solar wind stretches the Earth’s “magnetosphere” to form a “magnetotail”. When this tail is stretched too far, as a result of some magnetic storm on the surface of the Sun releasing excess wind, the tail snaps back toward Earth – sending a flood of charged particles into our atmosphere. [sketch 67]

The result is collisional excitation and collisional ionization, which is immediately followed by de-excitation, recombination, and cascade – all of which produce photons. So we see the sky glow. (In the southern hemisphere, it’s called aurora australis.)

- This section is relatively simple when compared with the reality [22]

- Homework.

  1. (8 points) It’s possible for the Earth’s magnetic field to reverse; the north and south magnetic poles exchange places. If this were to happen, could we still see aurora borealis? Could we only see aurora australis? If the Earth’s magnetic field disappeared for a year during the reversal, could we see any auroral displays – borealis, australis, or otherwise? Justify your answers.

  2. (6 points) Imagine that charged particles interacted with magnetic fields in such a way as to be able to cross the field lines but not move along them. Would there be any auroral displays – borealis, australis, or otherwise? Justify your answers.

---

[20] Consider the similarities to lightning.

[21] Inside the magnet, the lines run from S to N; outside they run around from N to S. Note that the Earth’s south magnetic pole is the geomagnetic north pole.

[22] APoD; image search “aurora”; WSS 100 1-4 (14’) (33’40”=12’05”); Dance of the Spirits by Alister Chapman, from 2012 January 24.
3.15 Doppler Shift

- [Doppler shift demonstrator (UNL), Doppler applet (CBU)]
- The Doppler effect is a measurable shift in f as a result of relative motion between the source (of waves) and the observer.

Imagine a car or train pass by you; there is a drop in pitch (not loudness!). Consider a wave: \( w, f \sim \text{pitch}; A \sim \text{loudness.} \) [sketch 68]

Consider water, sound, light.

Recall \( c = wf \), so \( v = wf \) is also true. (Be careful here, \( v \) is wave speed, not speed of relative motion between source and observer).

- A picture in your mind is useful... picture water waves, but be wary. There can be differences between some scenarios: stationary source with moving observer, moving source with stationary observer, or both moving.

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\[ \text{know because } c \text{ is constant and } c = wf \]
\[ \text{should be able to visualize} \]

Notice there is always a shift in \( f \).

Try to think and visualize until all of the elements of the table make perfect sense.

- The Dopper shift does not depend on relative distance; it depends on relative motion.

- Which lines show up in a spectrum tells us what the universe and its contents are made of; how lines are shifted tells us how the universe and its contents are moving! Consider spectra from the lab and three stars. [sketch 69]

- Reading.
  - TCPF2: Chapter 7, Section 1, page 116.

- Homework.
  1. (6 points) The Doppler effect takes on two forms: blueshift and redshift. Where do these names come from? How might it be possible to explain their significance in terms of an approaching or receding source of water waves? Is the water situation identical to the light situation? Why or why not?
  2. (6 points) If a light source moves away from you, you detect a redshift; if a light source moves toward you, you detect a blueshift. If the source is stationary, but you, the detector, are moving, do you detect a Doppler shift? Why or why not? Can you relate this to the water case? If so, how?
  3. (5 points) If a light source is directly north of you, and it is moving due west, what sort of Doppler shift (blue, red, or none) could you detect? Why? (Note: the wording of this question is exact.)

3.16 Parallax

- Parallax is used to measure distances to “nearby” stars.
- Hold your thumb out in front of you with your elbow locked, alternately looking at it with only one eye and then only the other. Notice how the apparent position of your thumb changes relative to the background. This is known as a parallax shift. Now try the same with your thumb half as far from your eyes. Notice the shift gets larger.
- The size of the parallax shift depends inversely on the distance between the observer and the observed. In the example above, this distance is between your eye and thumb. It also depends on the distance between the two locations of the observer. In the example above, this distance, or baseline, is between your eyes.

- Consider parallax using different student pairs (baselines) in the room to observe the location of a pen.

So it becomes clear that larger baselines are needed for more distant objects. When an object is very far away, the shift might be too small to measure; then we need a larger baseline.

- Consider using the Earth’s diameter as a baseline. But we can do better: Earth’s orbit. [sketch 70] The parallax angle is half of the shift.

- Consider an arcsecond: \( 1'' = \frac{1}{3600} \). What would a dime look like when viewed from a distance of 2 km? [sketch 71] An object can be so far away that its parallax angle is \( 1'' \); it’s distance is \( \sim 3.26 \) light years. This distance is defined as 1 parsec (which is short for parallax second).

In general, there is a simple formula relating the distance, in parsecs, to the parallax angle, in arcseconds: \( d = \frac{1}{p} \).

- Reading.
  - TCPF2: Chapter 12, Section 1, page 199.

- Homework.
  1. (4 points) If there were only one other star in the universe besides our \( \odot \), could the parallax effect be used to determine its distance? Why or why not?
  2. (5 points) If we wanted a parallax baseline larger than the diameter of the Earth’s orbit, we might consider placing a telescope on Mars. That is, we use one telescope on Mars while simultaneously using one telescope on Earth. Under what circumstances would this be an ineffective strategy? Under what circumstances would this be an effective strategy? Justify your answers.

3.17 Proper Motion & Radial Velocity

- Proper motion can be measured with two images taken one year apart. [sketch 72] (Why must it be one year?)

Consider three possible paths of a star that show the same proper motion. [sketch 73] How will we know which is the true space velocity?

- Radial velocity can be measured with Doppler shifted spectral lines. [sketch 74] (Recall that the size of the shift tells us how fast.)
• While proper motion is perpendicular to the line of sight, radial velocity is parallel to the line of sight. [sketch 75]

So we see that if we add the arrows together, we find that proper motion plus radial velocity equals the true space velocity.\(^{25}\n
• Homework.

1. (5 points) Parallax measurements and proper motion measurements must be made with deliberate delays in between observations. Which of the two requires the larger delay? Justify your answer.

4 Planets

4.1 Overview of Solar System Objects

• Our discussion of planets will be relatively brief. Please refer to the textbook for more details.

• Remember the order of the planets with a mnemonic device like “My very educated mother just served us nachos.”

• Planets are often studied in groups. Since the planets within a group often have several characteristics in common, our understanding of one planet can be enhanced by researching another. This approach is known as comparative planetology.

• The first group is the terrestrial planets and our Moon: Mercury, Venus, Earth, Mars, & Moon.

• The second group of planets is the jovian planets (a.k.a. giant planets, gas giants): Jupiter, Saturn, Uranus, & Neptune.

• Other classes of solar system objects include dwarf planets (Ceres, Pluto, Haumea, MakeMake, Eris, and maybe Sedna), moons in general (Earth has one, Mars has two, Jupiter has more than 60, Saturn has more than 60, Uranus has at least 25, and Neptune has at least 13), rings, asteroids, comets, and TNO’s (that is, trans-Neptunian objects, which include the Kuiper belt, the scattered disk, and the Oort cloud).

• Reading.

  – TCPF2: Chapter 4, Section 1.

5 Stars

5.1 Star Formation In Brief

• Macroscopically speaking, a galaxy is composed of three things: stars, dust, and gas.

  Check out APoD: image search “spiral galaxy”, “milky way”, & “eagle nebula”.

• While proper motion is perpendicular to the line of sight, radial velocity is parallel to the line of sight. [sketch 76]

So we see that if we add the arrows together, we find that proper motion plus radial velocity equals the true space velocity.\(^{26}\)

• Consider a star formation region. [sketch 76] Eventually, the cloud collapses due to gravity. [sketch 77] In addition to the star, other solar system objects (planets, moons, asteroids, and comets) form as part of this process.

• In the core of the collapsed cloud, the density and temperature have become much greater.

• When protons are fast enough to overcome their mutual electric repulsion, they can stick together (fuse).\(^{27}\) (It’s a bit like rolling two balls up a hill with a well on top?) [sketch 78]

Recall that a proton is a hydrogen nucleus, so when two protons stick together, it’s an example of nuclear fusion (not the same as nuclear fission). Nuclear fusion is what makes a star a star.

• Reading.

  – TCPF2: Chapter 4, Section 2.

5.2 Nuclear Fusion

• The principle underlying all nuclear reactions, fusion or fission, is the interchangability of mass and energy: \(E = mc^2\). The total amount of “mass-energy” in the universe is thought to be constant; it can be neither created nor destroyed.

• There are a few rules that go along with nuclear fusion reactions. Here we are concerned with two of them: conservation of charge and conservation of nucleons (a proton or a neutron is a nucleon). In physics, when something is conserved, the total amount doesn’t change.

• The most common nuclear fusion reaction in our Sun and in most stars is called the proton-proton chain reaction. We can imagine it in three stages, each of which obeys the rules.

  The first stage begins with two protons colliding, which become a deuterium nucleus (one version of heavy hydrogen), a neutrino (a nearly massless neutral particle, which happens to conserve spin), and a positron (this most common example of antimatter is just like an electron, but with opposite charge; it can also be thought of as an electron moving from the future to the present). The positron then meets an electron, annihilates with it, and forms two gamma rays. [sketch 79] Consider conservation.

  The second stage begins with a deuterium nucleus and a proton colliding and ends with a \(^3\)He nucleus and a gamma ray. [sketch 80] Consider conservation.

  The third stage begins with two \(^3\)He nuclei colliding and ends with a \(^4\)He nucleus and two protons. [sketch 81] Consider conservation.

• We can imagine all three stages together in one reaction which obeys the rules. [sketch 82] Consider conservation.

• Consider some details.

\[
6^1\text{H} + 2e^- \rightarrow ^4\text{He} + 2^1\text{H} + 6\gamma + 2\nu
\]

\(^{26}\)WSS 180 1-2 (11')

\(^{27}\)They do this by getting close enough for the strong nuclear force to take over. Did you ever wonder why, since like charges repel, the protons in a nucleus don’t repel each other?

\(^{25}\)This is just vector addition.

\(^{24}\)WSS 100 2-1 (8')
5.3 Limb Darkening

We can ignore the neutrinos and the electrons here. We can also subtract two protons from each side. So the reaction boils down to something less complicated.

\[ ^1H \rightarrow ^4He + 6\gamma \]

The essence of this is simple.

\[ \text{fuel} \rightarrow \text{exhaust} + \text{energy} \]

- It turns out that the mass of four protons (6.69 × 10^-27 kg) is more than the mass of the \(^4\text{He} \) nucleus (6.64 × 10^-27 kg). Where did the missing mass (.05 × 10^-27 kg) go? (It’s not related to the electrons that we ignored, they’re combined mass is only about .002 × 10^-27 kg.) It actually turned into energy! The amount of energy produced is about 4 × 10^{12} Joules, which is about one trillionth of a dietary calorie (Cal).

- The Sun’s luminosity (total power output) is about 4 × 10^{26} Watts (a Watt is one Joule per second). So how many reactions, at 4 × 10^{-12} Joules per reaction, must happen each second to produce this amazing power? The answer is 10^{38} reactions per second! And this rate lasts for ten billion years! So how much mass is converted to energy each second in our Sun? The answer is about 5,000,000 metric tons per second.

- The essence of this is simple.

5.4 Sunspots In Brief

- The solar atmosphere is somewhat ionized, radiatively and collisionally. So the gas contains charged particles. Recall that charged particles interact with \( \vec{B} \)’s.

- Consider the Sun’s (latitudinal) differential rotation, whereby the equator’s period is about 25 days while the period near the poles is about 35 days. As a result, the equatorial \( \vec{B} \) races ahead and even wraps around the Sun. \[ \text{sketch 87} \] The \( \vec{B} \) wraps, it twists. (consider a twisting cord). The \( \vec{B} \) forms a “kink” just as the cord does. Where this kink pops out of the Sun’s surface, we see sunspots. \[ \text{sketch 88} \]

- When the field is straight and calm, we say the Sun is at solar minimum. When the field is most wrapped and turbulent and the Sun has spots, we say the Sun is at solar maximum. \[ \text{sketch 89} \] This cycle takes, on average, 11 years; it is the sunspot cycle.

- Why do sunspots appear dark? Recall black body rule #1. Actually, sunspots aren’t dark; they’re just not as bright as the surrounding regions. Sunspot temperature is typically around 4000 K, which is about 2000 K cooler than the Sun’s usual surface temperature. This cooler temperature is the result of the Sun’s \( \vec{B} \) blocking rising convective cells. (Why would it block them?) Imagine a flashlight superimposed on a big searchlight.

- This section is relatively simple when compared with actual solar magnetic regions.

5.5 Exam II

- Recall that the temperatures of the core and surface are about 15 million K and 6000 K, respectively. So deeper is hotter. But we know hotter is brighter (bb rule #1). So if 1 is deeper than 2, then 1 is hotter than 2, and therefore 1 is brighter than 2. So the limb is darker.

- Check out APoD; image search “sun”.

- Homework.

  1. (6 points) If the core of the Sun were cool and the surface very hot, with a gradual change in between, would we see limb brightening instead of limb darkening? Why?

5.3 Limb Darkening

- Here we distinguish between the core & surface of the Sun and the center & limb of the Sun’s disk. \[ \text{sketch 83} \] Region 1 is the center and region 2 is the limb.

- Imagine a foggy day. You can see through the fog to some distance and then no farther. The Sun’s gaseous surface is similar. \[ \text{sketch 84} \] We can see deeper into the Sun in region 1, relative to region 2.

---

30 Consider granulation. What is convection? \[ \text{sketch 85} \] Our Sun has a convective mantle. \[ \text{sketch 86} \] While one surface region is hotter and brighter, the adjacent region is cooler and fainter.

29 The Sun also has radial differential rotation.

32 APoD; image search “sunspots”; WSS 100 1-3 (16’)

5.6 Stellar Evolution & the H-R Diagram

- **Stellar evolution** is the branch of astronomy that studies how stars change over time. (The Hertzsprung-Russell diagram, the cluster-aging technique, the life of our Sun, and the life of a supergiant are all under the umbrella of stellar evolution.)

- Consider some basic ideas relevant to the Hertzsprung-Russell diagram.

Imagine measuring luminosity and surface temperature (how?) of 100 stars chosen at random. You would have two columns of numbers, which you could plot against each other on a graph. [sketch 90] Notice the trend obeys black body rule #1.

Most (but not all) stars fit the trend. Why? (Imagine a sample of 100 people chosen at random. Place them into five bins: infant, child, adolescent, adult, & elderly. Which bin has the most people in it? Why?) For a star, the main sequence is the longest stage of its life (there are many stages). A star is on the main sequence if it’s fusing $H \rightarrow He$ in its core, and this leads to the special relationship between $L$ and $T$.

A star with $H$ fusion in the core will be in hydrostatic equilibrium; usually a star is in balance with itself. The inward force of gravity is balanced by the outward force related to the energy of nuclear fusion. [sketch 91] As a result, our Sun’s size stays relatively constant.

- Hydrostatic equilibrium lasts for about $10^{10}$ years for our Sun with core $H$ fusion. A very massive star about 120 $M_{\odot}$, will stay on the main sequence for about $3 \times 10^6$ years, while the least massive star, about .08 $M_{\odot}$, will stay on the main sequence for about $10^{12}$ years. [sketch 92] On the HR diagram, the more massive stars are at the top; the less massive at the bottom. [sketch 93] Is this reasonable?

When the fuel runs out, and there’s no more $H$ in the core, the star leaves the main sequence. But no one has ever lived long enough to see a star do this, so how can we know it’s true? (Have you ever watched someone go from birth to old age? No. So how do you know you’re going to get old?) It’s simple; we “connect the dots”, so to speak.

- Consider the cluster-aging technique. In a star cluster, the stars formed at nearly the same time. Imagine observing four clusters, and measuring $L$ & $T$, for 50 stars in each cluster, chosen at random. [sketch 93] We see the “main-sequence turnoff point” tells us the age of the cluster.

- Reading.
  
  - TCPF2: Chapter 8, Section 3 and Chapter 9, Section 1.

- Homework.
  
  1. (3 points) Briefly describe hydrostatic equilibrium.

2. (6 points) Pretend black body rule #1 tells us that cooler is brighter (instead of the actual hotter is brighter). Create a single HR diagram containing the real main sequence and the hypothetical main sequence that would occur as a result of this hypothetical rule #1.

3. (5 points) Generally, if one main-sequence star is hotter than another, it is also bigger. What if all main-sequence stars became the same size as our Sun, but kept their original masses and surface temperatures? Answer this question by creating one HR diagram containing both the real main sequence and the hypothetical main sequence that would occur if all main-sequence stars were the same size.

5.7 Life of Our Sun

- The Sun’s life can be described, and plotted on the HR diagram, in eight stages. [sketch 94]

- The first stage is the zero-age main sequence. This is the onset of $H$ fusion in the core, when the core temperature reaches about $15 \times 10^6$ K.

- The second stage, the main sequence, lasts about $10^{10}$ years. Here we have steady $H$ fusion in the core: the proton-proton chain.

- The third stage, the red giant branch, lasts about $10^9$ years. By the end of this stage, the radius is about $10^2 R_{\odot}$, the luminosity is about $10^4 L_{\odot}$, and the surface temperature is about 3000 K. So Mercury will be vaporized! Imagine visiting the Earth at this time; what would the Sun look like? The Earth will be uninhabitable.

Does it seem odd that the star is both cooler and brighter? This seems to conflict with black body rule #1. The answer is in the large radius. While $T_e$ has decreased only a little, $R$ has increased very dramatically.

The chain of logic follows something like this. The core runs out of $H$.

- So the core fusion ceases.
- So hydrostatic equilibrium is lost.
- So the core contracts.
- So the pressure rises in the $H$ shell around the He core.
- So the $H$ in the shell heats and fuses.
- So the inner envelope heats.
- So the envelope expands, becoming a giant.
- So the surface cools.
- So the surface gets red. [sketch 95]
- And the surface gravity becomes weak.
- And so the wind increases.

- The fourth stage is the helium flash, which lasts a few hours. It occurs when the core temperature reaches about $10^8$ K. The helium in the core begins to fuse and rapidly becomes a “thermonuclear runaway”.

The fusion reaction is called the triple-alpha process ($3\alpha$). We can imagine it in two stages. The first stage begins with a collision between two $^4He$ nuclei and results in a $^8Be$.

34 WSS 180 1-5 (11)
35 The “Eddington limit” means if there is too much mass, the fusion will be too great for the gravity; hydrostatic equilibrium will not be attained and the star won’t be able to form. This limit is around $300 M_{\odot}$.
36 The lifetime on the main sequence can be estimated with $t \approx 10^{10}$ yrs/$M^2$.
8Be nucleus. [sketch 96] Consider conservation. Since the 8Be nucleus is so unstable (it will decay in $10^{-16}$ seconds!), it should break apart into the 4He nuclei. But when the temperature is so hot – and the particles are so fast, a third 4He collides with the 8Be. This is the second stage, and the result is a $^{12}$C nucleus and a $\gamma$-ray. [sketch 97] Consider conservation. If another 4He collides with the $^{12}$C, it will form $^{16}$O.

Due to the tremendous energy released, the core is able to expand and the “degeneracy” is removed.

- The fifth stage, the horizontal branch, lasts about $10^8$ years. Hydrostatic equilibrium returns and there is steady helium fusion ($3-\alpha$) in the core. [sketch 98] Examples of such stars today are Albebaran in Taurus and Arcturus in Bootes. [sketches 99 & 100] Such stars have the same luminosity, but slightly different surface temperatures; this is the reason for the “branch”.

- The sixth stage, the asymptotic giant branch, lasts roughly $10^6$ years. The AGB star is larger and more luminous than a red giant and slightly cooler. Venus will be vaporized; the Earth may just barely escape total destruction.

The chain of logic for the AGB is very similar to the RGB, except that it begins with the core running out of He, and there are two fusion shells: H and He. Also, the shell burning is unstable, causing thermal pulses, which can lead to the envelope pulsating! [sketch 101]

- The seventh stage is the planetary nebula. This occurs when most of the mass of the star is ejected into space as an expanding gas shell. The relatively small, hot core that is left behind will emit much UV radiation, thereby causing radiative excitation and ionization in the gas shell. Of course, this will result in de-excitation, recombination, and cascade: all of which produce photons. Hence, the shell glows and is a PN. [sketch 102] (This has nothing to do with planets; the name comes from the look of the expanding gas shell when viewed with a small telescope.)

Did you ever wonder where the C in your DNA was built? Or the O in the air you breathe and the water you drink? Now you know!

- The eighth stage is the lone white dwarf, which is the hot core that’s left behind. It’s about the size of the Earth, with a surface temperature of about 25,000 K; the black body curve peaks in the UV. [sketch 103] Consider the density of about $10^3$ kg/cm$^3$.

Consider the strange idea of electron degeneracy, and how this purely quantum mechanical effect, which is not a force at all, is able to withstand the tremendous force of gravity. How bizarre! And yet, this has been confirmed through the consistency between observations and the Chandrasekhar limit, which states that $M_{\text{WD}} \leq 1.44M_\odot$ if the WD is made of C & O.

- Reading.
  - TCPF2: Chapter 9, Section 2, pages 152 - 155 and Chapter 10, Section 1, page 167.

- Homework.

5.8 Supergiants & Supernovae

- Some high-mass stars can become supergiants (15 $M_\odot$ to 120 $M_\odot$).

- Eventually, the H in the core runs out. The star exits the MS, becomes a hot, blue supergiant, and subsequently becomes a cool, red, He-burning supergiant. The size of the core is only about $0.1R_\odot$, but the size of the star is tremendous: about $10^4R_\odot$! If we replaced our Sun with a red supergiant, it’s surface would be at Jupiter! So we can fit a million Earths inside our Sun, but we can fit a billion Suns inside a red supergiant! Think of this next time you gaze at Betelgeuse in Orion or Antares in Scorpius. [sketches 104 & 105]

- The core of such a star exceeds the Chandrasekhar limit and cannot become a WD. There are several burning stages in a supergiant core. Each time a fuel source runs out, the ash of the reaction becomes the fuel for the next reaction at higher temperature. And an additional fusion shell will surround the core, thereby producing a layered structure like that of an onion.

Before the core H runs out, it burns for about $10^7$ years at a core temperature of near $10^8$ K. The subsequent core He-burning ($3-\alpha$) stage lasts about $10^6$ years at a core temperature of $10^8$ K.

The core C-burning stage, at about $10^9$ K, lasts only a couple hundred years. At this temperature, $^{12}$C fusion leads to $^{16}$O, $^{20}$Ne & $^{24}$Mg (a processes, a.k.a. He-capture reactions).

At this point, there is no C left in the core. The core Ne-burning stage, at nearly $2 \times 10^9$ K, lasts only about a year. At this temperature, $^{20}$Ne will fuse into $^{16}$O and $^{24}$Mg, and $^{28}$Si (photodisintegration and He-capture, respectively).

When all the neon in the core is gone, the O-burning stage ensues for about half a year. At a temperature of nearly $3 \times 10^9$ K, a set of reactions beginning with two $^{16}$O nuclei will result in the formation of $^{28}$Si and $^{31}$S.

\[^{40}\text{WU}\, 180\, 1-4\, (12)\]
The next reaction begins in the core at a temperature of nearly $4 \times 10^9$ K and lasts only a couple days. Here, a set of reactions involving $^{28}$Si nuclei will result in the formation of $^{56}$Fe.

- At this point [sketch 106] there is an Fe core, but no more fusion reactions will occur. A nucleus with 56 nucleons has the lowest mass per nucleon, and therefore any further fusion reactions would have to be endothermic.\(^{41}\)

So the core continues to contract and heat to such a degree that the Fe photodisintegrates and then electrons combine with protons to produce neutrons and neutrinos. [sketch 107] Subsequently, the core rapidly collapses (at nearly one quarter of the speed of light!) to such a small size that everything bounces out from the very center.\(^{42}\) Usually, a neutron star is left behind.

This rebound and the tremendous outward flux of neutrinos cause most of the star to explode outward. The energy of this event, produced by the gravitational collapse of the core, is more than 100 times what our Sun will generate over its entire MS lifetime! This event is a type II supernova.

- This outward shock wave induces all sorts of nuclear reactions, resulting in the construction of all elements heavier than Fe.\(^{43}\)

In the year 1054, the Chinese and the Anasazi both recorded a supernova; today we see the remnant as the Crab Nebula in the constellation of Taurus. (Why did the Europeans miss it?) What if Betelgeuse or Antares went off tonight? It would be ten times brighter than the full moon and might last a few months!

- Reading.
  - TCPF2: Chapter 9, Section 2, pages 155 - 159.

- Homework.
  1. (16 points) Consider part of the life of a proton. Begin with it in the photosphere of a newly formed 50 M\(\odot\) star and follow it into a supernova shell. Assume it does not leave as wind, but is ejected with the supernova. Consider the mass of the nucleus in which this proton resides and make a graph of this mass vs. time.
  2. (11 points) Consider part of the life of a proton. Begin with it in the core of a newly formed 50 M\(\odot\) star and follow it into a neutron star. Consider the mass of the nucleus in which this proton resides and make a graph of this mass vs. time.

5.9 Neutron Stars & Pulsars

- The core left behind after a type II supernova is likely to be made mostly of neutrons, and so it’s called a neutron star. Due to neutron degeneracy, the mass must be less than about 3 M\(\odot\). The size of a neutron star is only about 10 km across. Therefore, the density is about $10^{11}$ kg/cm\(^3\)! Neutron stars have very short rotation periods – typically they rotate 30 times per second. They also have very strong magnetic fields – typically $10^8 \vec{B}\odot$. If the magnetic axis is not aligned with the rotation axis, the electrons and positrons in the $\vec{B}$ generate synchrotron radiation, which is aimed outward along the magnetic axes. [sketch 108] If one of the axes points toward the earth once each rotation, then it will behave like a lighthouse; in this case, we call it a pulsar.\(^{44}\)

- Reading.
  - TCPF2: Chapter 10, Section 1, pages 169 - 170.

- Homework.
  1. (3 points) Briefly describe the difference between the “pulses” of an AGB star and the “pulses” of a pulsar.
  2. (6 points) A typical pulsar may have a rotation period of .03 seconds. Imagine such a pulsar had a precession period of 300 seconds. Would such a neutron star still be a pulsar? If so, would the time between pulses become greater, or less, or would the time stay the same (compared to no precession)? If greater or less, how much time would be between pulses? Justify your answers.

5.10 Binary Stars

- It’s not unusual for two stars to orbit each other, perhaps without any planets around either star. This type of system is called a binary star. It’s also possible to have a multiple star system.\(^{45}\) Binary stars come in three classes: visual, eclipsing, & spectroscopic.

- Usually, a binary star is so far away that even the biggest telescope will have insufficient angular resolution to distinguish the two stars. In the rare case when it’s possible to resolve a binary, we call it a visual binary.

- If the orbital plane of the binary intersects with the Earth, then we can observe eclipses. We call this an eclipsing binary. Such a system produces a light curve. Consider an example with a smaller, hot star and a larger, cooler star. [sketch 109] What would be the shape of the light curve?\(^{46}\)

- Even if the system can’t be resolved and doesn’t produce eclipses, we can still conduct revealing observations using spectral analysis. Such a system is called a spectroscopic binary. Here, we measure Doppler-shifted spectral lines, and the two sets of lines move opposite to each other. That is, when one star is moving away from us, the other is moving toward us – and vice-versa.

- Reading.
  - TCPF2: Chapter 8, Section 2, page 136.

- Homework.
  1. (16 points) Recall the light curve in the section Binary Stars. The system has a smaller, hot star and a larger, cool star. The orbital plane contained our line of sight.

\(^{41}\)The nuclei of 56 nucleons is also a dead end for fission reactions.

\(^{42}\)The halt of the collapse is probably a combination of neutron degeneracy and a repulsive neutron-neutron interaction mediated by the strong nuclear force.

\(^{43}\)WU 180 2-4 (15')

\(^{44}\)WU 100 3-3 (12')

\(^{45}\)Consider α-Centauri, or Castor in Gemini.
Both stars display limb darkening. The orbits are circular.

Sketch four similar light curves, drawing two full consecutive periods for each. Assume everything is nearly the same as the system discussed in class: except in each case there is one thing different, as follows. (a) The hot star is larger and the cool star is smaller. (b) The stars are the same size, (c) Neither star displays limb darkening, or (d) The orbits are highly elliptical. Justify your answers.

5.11 Novae
- Imagine living 2000 years ago in Rome, where you watched the sky every night. You learned the constellations. One evening, when you were gazing at your favorite constellation, you see there is a new star that wasn’t there before. You say, “Nova!”

But today we know that star formation is a very slow process, and doesn’t happen overnight. So how could this be?

- Most stars are in binary (or multiple) star systems. The more massive star becomes a RG and then a WD first. If the pair is close, the WD causes tides and mass transfer. An accretion disk forms. [sketch 111] When the mass arrives on the WD, the density increases and a thermonuclear explosion occurs. New material is blown off, and we see a nova.

5.12 Cosmic Recycling
- Where did the carbon and oxygen atoms in our bodies come from? Our iron atoms and our heavier elements?

The star-gas-star cycle is self-explanatory. Stars end their lives as planetary nebulae or supernovae, sending their “newly constructed” elements back to the interstellar medium. Some of the ISM becomes interstellar dust. Subsequently, this interstellar dust and gas collapses to form new stars. The cycle continues. We are recycled star material.

- What if some of our protons could tell their stories? Each would have its own unique 13.8 billion-year story to tell. If we could speak with one of our protons, we could ask it questions. Where were you ten billion years ago? Six billion? Of how many stars have you been a part? Where were you one billion years ago? Ten thousand? One hundred? One year ago? Where do you see yourself in ten billion years?

Each of us is an astounding collection of nearly 10^28 protons — many of the protons having journeys as old as the universe — that have come together after billions of years. How amazing!

- When I look into the sky I know the stars built you and me, and one day you and I will build them in return.

5.13 Black Holes
- If a supernova leaves behind a core that exceeds the neutron degeneracy limit, then a black hole can form. We consider the black hole twice: a classical approach and a modern understanding. We also consider evidence of the existence of black holes.

The classical approach considers the stellar core in a continual state of collapse; the smaller it gets, the faster it gets smaller. Zero size implies the existence of a singularity, at which the density, gravitational force, and escape velocity are all infinite. Why? Escape velocity is \( v_{\text{esc}} = \sqrt{2GM/R} \).

At any distance away from the singularity, \( F_j \) & \( v_{\text{esc}} < \infty \). At greater distances from the singularity, \( F_j \) & \( v_{\text{esc}} \) get less. [sketch 112] Consider some distance from the singularity at which \( v_{\text{esc}} \) has decreased down to \( c \), the speed of light. Here we find \( R = 2GM/c^2 \). Why? What does this mean? This distance is known as the event horizon. Our Sun will never become a black hole because it doesn’t have enough mass. But if we pretend that suddenly our Sun collapsed and became a black hole, what would happen to the Earth’s orbit? Why? We note that the strength of a black hole is not in its mass, but in its small size.

A modern understanding includes Einstein’s general theory of relativity (GR). Note that GR tells us that spacetime is curved, and this curvature slows the passage of time: also note that GR tells us that gravitation is curvature and curvature is gravitation! The event horizon is known as the Schwartzschild radius, \( R_{\text{Sch}} \).

Consider infinite curvature in one dimension and in two dimensions. [sketches 114 & 115] A singularity is infinitely curved, four-dimensional spacetime.

The evidence for black holes is, of course, indirect because we can’t see them directly — no light can come from a black hole. Consider the accretion disk around a black hole in a binary system. [sketch 116] Infalling matter can be accelerated to very large velocities, hence the gas is hot (sometimes millions of degrees) and therefore glows. We can measure the blackbody curve of the disk and find x-rays.

Consider a black hole in a spectroscopic binary. But in this case there is only one set of Doppler-shifted spectral lines.

46If enough material accumulates on the WD to overcome the Chandrasekhar limit and initiate collapse, the result is a type Ia supernova.

47WU 180 2-1 (113)

48For a 10M⊙ black hole, \( R \approx 3,000 \) km.

49This is based on, but more advanced than, his special theory of relativity.
By studying the motion of the spectral lines, the mass of the unseen companion can be estimated. When we put together these two methods for the same object, we can be fairly certain we are dealing with a black hole.

- **Reading.**
  - TCPF2: Chapter 10, Sections 2 - 3.

- **Homework.**
  1. (5 points) Why is a black hole black? Why is it considered a hole? How is the name “black hole” related to escape velocity? What is an event horizon? Regarding the existence of a singularity, how does the classical approach to a black hole contradict our modern understanding?
  2. (10 points) The New Horizons probe had a speed of about 15 km/s. The speed of light is about 20,000 times faster than this. At the probe’s speed, it would be able to escape a black hole if it were much farther away than the event horizon. How much farther? Give your answer in terms of Schwartzschild radii.

### 5.14 Gravitational Redshift

- When a rock is tossed upward from the surface of the Earth, it slows as it rises. One way of looking at this is to realize that gravity is working against the rock and therefore steals the rock’s energy.\[ K = \frac{1}{2}mv^2 \]

- Consider a much stronger gravitational force, like that at the surface of a neutron star. Gravity will also work against light moving upward from the surface of the neutron star. However, we know (from Einstein’s special theory of relativity) that light cannot slow down as it moves upward. So the only way for light to lose energy is by decreasing its frequency – or, equally, increasing its wavelength.\[ \text{[sketch 117]} \]

- Of course, a decrease in frequency is a redshift. And in this case, the redshift is caused by gravity (as opposed to relative motion between source and observer).

- **Reading.**
  - TCPF2: Chapter 10, Section 2, page 175.

- **Homework.**
  1. (5 points) Imagine you could stand on the surface of a neutron star, or hover just above the event horizon of a black hole, and survive. Imagine also that you had a telescope with you that allowed you to see our Sun. What color might it be? Justify your answer.

### 6 Galaxies

#### 6.1 Overview of Galaxies

- Galaxies come in four basic types: elliptical, barred spiral, unbarred spiral, and irregular.\[ \text{[sketches 119, 120, 121, & 122]} \]

- All types come in a wide range of sizes. Our Milky Way is a barred spiral galaxy.

- **Reading.**
  - TCPF2: Chapter 11, Section 2, pages 189 - 190.

#### 6.2 AGN

- A quasar\[ \text{[11]} \] is a type of active galactic nucleus, or AGN – brighter than most.

- When a supermassive black hole at the center of a galaxy forms an accretion disk, collimated jets can result.\[ \text{[sketch 125]} \]

- This has been likened to using a fire hose to fill a dog’s water bowl.

- The inner part of the accretion disk is very hot and, consequently, very bright. (Why?) If our line of sight is such that we see to the center of the accretion disk, then we see a relatively bright AGN.\[ \text{[sketch 126]} \]

- If our line of sight is such that we are looking along one of the jets, then we see a blazar\[ \text{[52]} \]

- **Reading.**
  - TCPF2: Chapter 11, Section 3.

#### 6.3 Dark Matter

- Dark matter shows up in two arenas: galactic and extragalactic. The data show that about 10% of the mass in a galaxy is seen and 90% is dark matter. In clusters of galaxies, the data show that much less than 10% in a cluster is seen, and nearly 98% is dark matter!

- The galactic dark matter problem arises from rotation curves of spiral galaxies. There is a significant difference between those predicted and those observed.\[ \text{[sketch 128]} \]

- (Consider Kepler’s third law.) There must be a tremendous amount of mass, or “matter”, present to provide the gravity needed to produce the observed rotation curves. Such a dark matter “halo” is thought to be much larger than the visible part of any galaxy.\[ \text{[sketch 129]} \]

- Since this matter has not been detected at any wavelength, we call it “dark”.

- Elliptical galaxies also exhibit dark matter because the hot gas in the galaxy should be escaping, but it’s not.

- The velocities of galaxies orbiting in a cluster allow us to calculate the mass of the cluster. This mass can also be measured by studying x-rays from hot gas in the cluster. The mass of a cluster can even be measured through gravitational lensing (in accordance with Einstein’s general theory of relativity).\[ \text{[sketch 130]} \]

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50 Energy of motion is called kinetic energy: \[ K = \frac{1}{2}mv^2 / 2 \].

51 The word is an abbreviation of quasi-stellar radio source.

52 The word is meant to combine two classes of phenomena: quasars and BL Lac objects.
three techniques give mass estimates that are in general agreement – a fine confirmation of the dark matter in clusters.

- There have been several hypotheses including the following: asteroids or comets, pebbles, dust grains, red dwarfs, WIMPs, brown dwarfs, MACHOs, ICM, and WHIM (the last two, strictly speaking, aren’t even “dark”).
  - Asteroids, comets, pebbles, and dust grains can all be ruled out because their chemical composition contains too many heavy elements – we know from other areas of astrophysics that the universe is mostly made of H and He. Red dwarfs are smaller than the smallest known stars, and have perhaps 10% of the Sun’s mass and 1% of the Sun’s brightness; but observations of globular clusters indicate that 20% of the Sun’s mass is the lower limit.
  - WIMP stands for weakly interacting massive particle; these particles are heavier, but less interactive than neutrons. It’s possible that these particles haven’t been discovered yet and are, therefore, totally unknown. And because they’re weakly interacting, they may be extremely difficult to detect.
  - Brown dwarfs almost became stars, but they didn’t because they don’t have enough mass. MACHO stands for massive compact halo object. Examples of possible MACHOs are white dwarfs, neutron stars, and black holes in the halo rather than the disk of the galaxy. As all of these objects are “failed” or “dead”, they can be very difficult to detect. But there is a technique, based on gravity that has shown that MACHOs make up perhaps 20% of dark matter in the Milky Way.
  - ICM stands for intracluster medium, which is a hot (≈ 10⁸ K) gas that is abundant enough to be a few times more massive than the visible part of a cluster. (Is that enough?) WHIM stands for warm-hot intergalactic medium, which comprises large clouds of gas that may account for up to 10% of measured dark matter. (Is this enough?) (The distinction between “intra-cluster” and “intergalactic” is as follows. The former is also intergalactic, but exists only within the cluster, while the latter is also intracluster, but extends well beyond the cluster.)

- Reading.
  - TCPF2: Chapter 14, Section 1.

- Homework
  1. (2 points) Considering MACHOs and ignoring WIMPs, What percent of our galaxy’s mass consists of MACHOs? Justify your answer.
  2. (5 points) Approximately what percent of our local cluster’s mass may be accounted for by the ICM and the WHIM combined? Justify your answer.

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7 Cosmology

7.1 Hubble’s Law & Hubble Distance

- Cosmology is the science of the universe as a whole. The universe is expanding; spacetime itself is expanding.
- Hubble’s law is \( v = H_0d \), or equivalently, recessional velocity equals the Hubble constant times distance. The recessional velocity refers to the speed between our Milky Way and the observed distant galaxy; the Hubble constant (which is constant across space, not time) is about 70 km/s/Mpc. The distance is that between our Milky Way and the observed galaxy.

Note the interesting units in \( H_0 \). First, we must understand that a megaparsec is \( 10^6 \) parsecs, and a parsec (short for “parallax second”) is about 3.26 light years. So we see that if a galaxy is 2 Mpc away, then it’s recessional velocity is 140 km/s. And we see that if a galaxy is 10 Mpc away, then its recessional velocity is 700 km/s.

The Hubble distance is the distance to an object that has recessional velocity equal to \( c \). It’s equal to approximately 13.8 billion light years.

- Hubble’s law is isotropic, so it’s the same in all directions. Does this imply we’re at the center of the universe? It might seem odd at first, but let’s consider raisin bread. We assign a number to each of four raisins across the bottom of the bread, and bake the bread for one hour. [sketch]

Of course, the raisins don’t move much relative to the bread while it expands. Likewise, clusters of galaxies aren’t moving much through space; it’s the space itself that expands.

Consider the view from raisins numbered 1 & 2. We see that isotropy does not imply we’re at the center of the universe.

- Reading.
  - TCPF2: Chapter 12, Section 1, pages 202 - 203 and Section 2, pages 204 - 206.

- Homework
  1. (4 points) Imagine \( H_0 = 100 \text{ km/s/Mpc} \). What would be the recessional velocity of a galaxy 10⁹ parsecs away? Justify your answer.

7.2 Cosmological Redshift

- Consider one supercluster (a cluster of clusters) of galaxies moving away from another. Imagine a photon headed from one to the other. It will take a very long time for the photon

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53Here, weakly refers to the strength of one of the four fundamental forces in the universe: the weak nuclear force. A neutrino is an example of a weakly interacting particle.

54Microlensing is a “small” version of gravitational lensing.
to reach its destination, and during this time the universe will expand significantly. [sketch 132]

Consider a wavy line on a deflated balloon. What happens when the balloon is inflated? [sketch 133]

So the photon will increase its wavelength while it travels – or equivalently, decrease its frequency. This is a redshift, and it’s caused by the expansion of the universe.

- The cosmological redshift formula is not the same as the Doppler shift formula since the former must account for cosmic expansion. The formula for cosmological redshift takes into account Einstein’s general theory of relativity, whereas the formula for relativistic Doppler shift only takes into account Einstein’s special theory of relativity. The two formulas only produce similar answers for nearby galaxies.

- Reading.
  - TCPF2: Chapter 12, Section 2, page 207.

7.3 Big Bang

- As time continues forward, clusters and superclusters recede from each other. What if we could watch the universe with time going backward? We would see everything getting closer. [sketch 134] If we watch long enough, we should see everything in the universe so close together that it’s all at the same location: the big bang.

- As a simple example of the importance of $H_0$, let’s consider the easiest formula in physics. Velocity equals distance divided by time: $v = d/t$. (Your speedometer reminds you of this formula everytime you look at it, right?) Of course, we can solve for time: $t = d/v$. And where have we recently discussed distance and velocity together in a formula? Hubble’s law: $v = H_0 d$. We can rearrange this to find $1/H_0 = d/v$. Therefore, we find that $t = 1/H_0$, meaning we can make a simple estimate of the age of the universe!

- Estimate...

- Reading.
  - TCPF2: Chapter 12, Section 2, page 206.

7.4 Cosmic Microwave Background

- When we take a picture of the universe, of space itself, we find black body radiation. The curve peaks at a wavelength of about 1.1 mm, which is in the microwave band. This wavelength gives us the temperature of empty space itself: about 2.73 K.

- These microwaves are actually left over from the big bang. Over the past 13.8 billion years, the universe has expanded and therefore cooled. This cosmic microwave background radiation, or CMBR, is very strong evidence of the big bang.

- Reading.
  - TCPF2: Chapter 13, Section 2, pages 219 - 223.

7.5 Exam III

Exam 3 covers material between exam 2 and here.

7.6 Final Exam

The final exam is cumulative.

57 We are not talking about the photon’s reference frame.
58 If $z$ is the redshift, then $1 + z = R(t_{\text{obs}})/R(t_{\text{em}})$. Here, $R$ is proportional to the scale factor, which is related to the ratio of sizes of the universe at two different times.
59 If $z$ is the redshift, then $1 + z = \sqrt{(1 + v/c)/(1 - v/c)}$.
60 Consider a galaxy at the Hubble distance. The Doppler shift formula would predict the wrong result: $z = \infty$. The cosmological redshift formula predicts the correct result: $z \approx 1.5$.
61 WSS 170 7-1, 7-2 (27") (skip at 26'45" = 11'15")
62 This name was coined by an opponent of the theory, but now we seem to be stuck with it.
63 The CMBR has travelled further than the Hubble distance, and it has a redshift of 1000. The plasma that emitted the CMBR that we see today was travelling away from us at 50c when the radiation was emitted.
64 WU 170 4-4, ALL 4-5 (28")