Principles of Astronomy: Possible Topics

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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[^1].)

  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[^2].

- 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, .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]: httwins.net; The Known Universe by AMNH; cosmic eye; atlasoftheuniverse.com; Cosmic Voyage.
Dec. 31, 11:58 p.m.: first modern humans
Dec. 31, 11:59:25 p.m.: rise of agriculture
Dec. 31, 11:59:49 p.m.: pyramids at Giza
Dec. 31, 11:59:59 p.m.: Kepler, Galileo

- 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></td>
</tr>
<tr>
<td>revolution</td>
<td>60,000 mph</td>
<td>26,000 yrs</td>
</tr>
<tr>
<td>galactic orbit w/ “bounce”</td>
<td>600,000 mph</td>
<td>1 year</td>
</tr>
<tr>
<td>Milky Way toward Andromeda</td>
<td>180,000 mph</td>
<td>$230 \times 10^6$ yrs</td>
</tr>
<tr>
<td>expansion of universe</td>
<td>$v = H_0r$</td>
<td></td>
</tr>
</tbody>
</table>

- Reading.

- TCPF2: Chapter 1, Sections 1 - 2.

- 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 Sun’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 Sun, 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 Sun, 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 theory (like Ockham’s Razor).

What does *simple* mean[3] 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 wrinkled piece of paper. 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.”[4]

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 3, Section 2.

- Homework.

[3]In the philosophy of science, “simple” does not imply “easy to understand”.

[4]This is known as “Newton’s Flaming Laser Sword”.
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 Basics

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 3]

• 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 ⊙ precesses like a top, once every ~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

2.4 Appearance of Stars

• 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 Seasons

• Consider how the visible constellations change with the seasons.

• Temperatures.

Why is it hotter in summer? (It’s not because the ⊙ is closer to the ⊙; perihelion is in January.) There are three ways to think about the answer, all of which involve the 23.5° tilt of the ⊙’s axis relative to the ecliptic. First, more of summer hemisphere is receiving sunlight. [sketch 11] Second, any location in the summer hemisphere receives more hours of sunlight per day. [sketch 12] Third, the summer hemisphere receives more direct sunlight. (Consider the overhead projector...)

• Reading.

– TCPF2: Chapter 2, Section 1.

• Homework.
1. (5 points) If the tilt of the Earth’s axis were 90°, would we still have four seasons? Would the changes between summer and winter be more extreme, less extreme, or non-existent? Justify your answers.

2.6 Lunar Phases

- prerequisite: Sky Coordinates

- There are eight phases of the Moon: new, waxing crescent, first quarter, waxing gibbous, full, waning gibbous, third quarter, and waning crescent. [sketch 13]

- These phases are the result of the changing position of the Moon relative to the Earth and the Sun. [sketch 14]

- 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 15, 16, & 17]

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 18]

- 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) If you are in Pacific Beach at night, and you see a crescent moon with an altitude of 10° and an azimuth of 270°, which crescent moon do you see and what time must it be? (Please draw diagrams with your answer.)

2.7 Days & Months

- prerequisite: Lunar Phases

- The *sidereal day* is one full rotation of the Earth, 360°. It lasts about 23h56m.

The *solar day* is from noon to noon. It lasts about 24h. [sketch 19]

- *Sidereal* means “by the stars”. The *sidereal month* is one full revolution of the Moon, 360°. It lasts about 27.3 days.

- *Synodic* means “coming together”. The *synodic month* is one complete cycle of phases. It lasts about 29.5 days. [sketch 20]

- Homework

  1. (5 points) If the Moon were orbiting the Earth in the direction opposite to the true direction (everything else being the same), how long would the sidereal and synodic months be? Why?

2.8 Eclipses

- prerequisite: Lunar Phases

- Two types of eclipses\(^5\) are solar and lunar. [sketches 21 & 22]

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 23] The Moon’s orbital plane is tilted at 5° 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?

2.9 Retrograde Motion

- A planet is a “wanderer”; Mercury, Venus, Mars, Jupiter, and Saturn were known to the ancients. [sketch 24]

- Planets normally go from W to E, but sometimes they go E to W. How could this happen? Epicycles? (Is the map backward?) [sketch 25]

- 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\(^6\) is an *apparent* backward motion. We on the ⊙ pass a slower planet. [sketch 26]

- Reading.
  - TCPF2: Chapter 2, Section 3.

- Homework.

\(^5\)WSS 100 1-1 (10')

\(^6\)WSS 100 2-2 (11')
1. (3 points) Will Jupiter enter retrograde motion more or less frequently than Saturn, as seen from Earth? Why?

2. (6 points) During the span of one of Jupiter’s orbits about the Sun, how many instances of retrograde motion could a person on the Earth see while observing Jupiter? Justify your answer.

### 2.10 Kepler’s Laws of Planetary Motion

- **First.** The law of ellipses: a planet orbits the ☉ in an ellipse with the ☉ at one focus. [sketch 27]
  - What exactly is an ellipse? (Consider 2 nails & string.) [sketch 28]
- **Second.** The law of equal areas: a “planet-Sun line” sweeps out equal areas in equal times. [sketch 29]
- **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.\(^7\) 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 30]

- **Reading.**
  - TCPF2: Chapter 3, Section 1, pages 39 - 40.

- **Homework.**
  - 1. (5 points) Planet A’s orbital period may be observed from the Earth; roughly how long is this period? Given this period, show (mathematically) how Kepler’s 3rd law may be used to derive Planet A’s distance from the Earth. (Planet A can be either Jupiter, Saturn, Uranus, or Neptune.)

### 2.11 Newton’s Laws of Motion

- **First.** The law of inertia: left undisturbed, a body at rest will remain at rest and a body in motion will remain in motion in a (straight) line.
  - Inertia is a body’s resistance to acceleration. Acceleration is a change in speed or direction.
- **Second.** \( F = ma \): force equals mass times acceleration.\(^8\)
  - Mass and weight are not the same. Weight depends on location; mass doesn’t. Weight is a force.
- **Third.** Action equals reaction: for every force applied to a body, there exists an equal and opposite force.
  - Consider a collision between billiard balls. [sketch 31]

- **Reading.**
  - TCPF2: Chapter 3, Section 1, Figure 3.8.

### 2.12 Newton’s Universal Law of Gravitation

- \( F = GMm/d^2 \)
  - 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\(^9\) including weight.

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

- **Homework.**
  - 1. (6 points) The mass of Mars is roughly 11% of the Earth’s mass. If you could visit Mars, would your weight be 11% of your weight on Earth? If not, would your weight be more or less than 11% of your weight on Earth? Justify your answer using \( F = GMm/d^2 \).

### 2.13 Tides

- **prerequisite:** Lunar Phases
- **prerequisite:** Newton’s Universal Law of Gravitation

- If high tide is at noon on one day, then high tide is at 12:50 pm the next day. If the Moon rises at 6 pm on one day, then it rises at 6:50 pm the next day. There is an apparent connection between the tides and the Moon, and since this observation requires no technology, humans have been aware of it for a very long time. But nobody understood this connection until Newton announced his U. L. of G.
  - Does the Moon really orbit the Earth? The answer is no, it actually orbits the Sun. What is the center of mass? (Consider two unequal masses on a balance [sketch 32]) Consider the Earth - Moon system. The center of mass orbits the Sun along the ellipse, while the Earth and Moon follow sinusoidal paths around the Sun. [sketch 33]
  - We don’t feel the average gravitational force exerted on the Earth because we’re on it. We basically feel what’s left over. That is, subtract the average from the actual and see what remains.
  - The tidal force at some location on the Earth is equal to the force from the Moon at that location [sketch 34] minus average force from the Moon (averaged over all locations). [sketch 35]
  - The tidal force\(^10\) tries to stretch and compress the Earth.\(^11\)
  - Consider tidal bulges.\(^12\) [sketch 36] An alternate way to think of it is that while the close side of the Earth is pulled more strongly, the far side is being thrown of by the centrifugal effect as the Earth goes around the center of mass of the Earth-Moon system.
  - There are lunar tides, and there are also solar tides. The combination of these two leads to spring tides and neap tides. [sketch 37]

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

\(^8\)Actually \( F = dp/dt.\)

\(^9\)WSS 180 6-1 (15’), WU 100 3-1, 3-2 (25’)

\(^10\)WSS 120 4-5 (12’)

\(^11\)More accurately, differential force fields tend to stretch things.

\(^12\)Consider tidal lock.
• More realistically, the non-ideal case can include several complications, such as continents and other land masses impeding flow, weather, ocean depth and shape of coastline and the friction of water with the ocean floor and with itself.

• Reading.
  – TCPF2: Chapter 6, Section 1, pages 101 - 102.

• Homework.
  1. (5 points) Describe the shape of the Earth’s tidal bulge four days after new moon; ignore any lag due to friction. Justify your answer.

3 Fundamental Concepts

3.1 Electromagnetic Radiation in Brief

• 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 $c \approx 300,000$ km/s. This is like going around the $\oplus$ 7 times in one second.

• Light is a wave. (Consider a sine wave, not a breaking wave.) [sketch 38] 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 39] Generally, $c = w f$.

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

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

• Homework.
  1. (3 points) The following are the bands of light that we discussed. Please list them in order of decreasing wavelength (i.e., start with longest wavelength). [gamma-rays, infrared, microwave, radio, ultraviolet, visible, x-rays]

3.3 Observing Instruments & Techniques

• prerequisite: Electromagnetic Radiation

• Two types of optical telescopes are the reflector (uses a mirror) and the refractor (uses a lens). [sketches 44 & 45]

• Interferometry is used to improve angular resolution, for which smaller is better. (ang. res. $\sim w/D$) Consider head-lights at night up close or far away. [sketches 46 & 47]

• 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” [47]

• Why have a space telescope? Light pollution happens when city lights reflect back down from our atmosphere. [sketch 48] Scintillation (“twinkling”) includes image flickering and jumping around. [sketch 49]

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

• Homework.
  1. (3 points) If a reflector and a refractor are the same path? Justify your answer.

13 google search “bay of fundy”
14 Viscosity is the friction of a fluid with itself.
15 We may compare interference and diffraction with the photoelectric effect and the behavior of CCD’s.
16 All these years this amazing object, light, has been all around you; did you ever stop to consider its true nature?
17 WU 100 4-3 (9')
3.4 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. °F, °C, K.

<table>
<thead>
<tr>
<th>scale</th>
<th>freeze</th>
<th>boil</th>
</tr>
</thead>
<tbody>
<tr>
<td>°F</td>
<td>32</td>
<td>212</td>
</tr>
<tr>
<td>°C</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>K</td>
<td>273</td>
<td>373</td>
</tr>
</tbody>
</table>

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.

- Reading.
  - TCPF2: Appendix C, Section 6.

3.5 Thermal Radiation

- prerequisite: Electromagnetic Radiation

- prerequisite: Temperature

- 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. 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). These curves show peaks for radiation influenced by the air in our atmosphere. [sketch 50]

  Three rules go along with the curves: hotter is brighter, hotter peaks at shorter wavelength, and hotter is brighter at all w’s.

  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. [21]

18 The curves are described by the function

\[ B(w) = \frac{2hc^2}{3\pi^5} \frac{1}{w^5} \]

19 12000 K peaks in the UV; 3000 K peaks in the IR.

20 WU 100 4-1, 4-2 (21’)

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

3.6 Scattering

- prerequisite: Electromagnetic Radiation

- What is it? Photons bounce off of tiny particles such as atoms, molecules, microscopic dust. [sketch 51]

  Why does blue scatter more than red? It’s related to \( 1/w^4 \). Consider ratios. [sketch 52]

- 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 53]

  Consider photons at sunset [22] [sketch 54]

- Why isn’t the sky purple? Consider the BB spectrum of the \( \odot \) and the eye’s sensitivity. [sketches 55 & 56]

  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 \( w \)? What would be the color of the setting sun in this case? Justify your answers.

3.7 The Classical Atom

- “Classical” implies an older, less accurate, but simpler idea. Consider a simple atom: nucleus and electron. [sketch 57]

- 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? \( ^1H, ^2H, ^3He, ^4He, ^3He^+, ^3He^- , ^8Li, ^{60}Fe^{++} \) 

  p⁺: a.n.
  n: a.w. - a.n.
  e⁻: a.n. - a.c.

- Homework.

  1. The green flash is a well-known phenomenon, but not as simple as many think. It’s more than just refraction and chromatic dispersion. To be seen with the unaided eye, a mirage is required for vertical magnification, and the observer must be in a cooler layer above a warmer layer.
3.8 Quanta, Absorption, & Emission

- prerequisite: Electromagnetic Radiation

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

Only certain levels are allowed for the electron; anything in between is forbidden. [sketch] This is the Bohr model of the atom.

The atom can only have specific quantities of energy. 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 instantly 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 electron jumps up to a higher level; this is absorption. [sketch]

\[ E = hf \]

\( E \) 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 electron 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, electron 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.

Emission of a photon occurs when an electron jumps to a lower level. This is the opposite of absorption. [sketch]

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

Emission is basically electron down, photon out.

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

3.9 Spectral Lines

- prerequisite: Thermal Radiation

- prerequisite: Scattering

- prerequisite: Quanta, Absorption, & Emission

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

A continuous spectrum is a blend – no gaps between the colors. [sketch]

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.
3.10 Ionization, Recombination, & Cascade

- prerequisite: Quanta, Absorption, & Emission

- **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? Consider stepping halfway to the wall and 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 66]

  Ionization is basically photon in, $e^-$ out. [Sketch 67] The result is 1 ion & 1 free $e^-$.  

- **Recombination** is the opposite of ionization. It is basically $e^-$ in, photon out. [Sketch 68]

  Sometimes the recombining $e^-$ lands in an excited state, rather than the ground state. It will then proceed to jump down level by level, releasing a photon at each jump. This series of jumps is known as a **cascade**. [Sketch 69]

3.11 Collisional vs. Radiative Processes

- prerequisite: Ionization, Recombination, & Cascade

  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 70 & 71]

- There is also collisional de-excitation. [Sketch 72]

- 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 Magnetic Fields

- The abbreviation used is $\vec{B}$.

  How shall we represent something invisible? With $\vec{B}$ lines. [Sketch 73]

  Consider a sketch of a river showing a “velocity field” of water flows. [Sketch 74] 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 75] The lines represent the shape of the force field and the “polarity” of the force. [Demonstration]

- What happens if we break a magnet in half? What about magnetic splinters, atoms, and subatomic particles? [Sketch 76]

  Charged particles interact with $\vec{B}$’s. They can run along them, but they can’t freely cross them. [Sketch 77]

3.13 Doppler Shift

- prerequisite: Spectral Lines

- prerequisite: Collisional vs. Radiative Processes

- [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: $w, f \sim$ pitch; $A \sim$ loudness. [Sketch 78]

  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).

  [24] Recall 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 65] 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 one other 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.

  [25] 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.
• 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.

<table>
<thead>
<tr>
<th></th>
<th>stat. so. mov. obs.</th>
<th>mov. so. stat. obs.</th>
<th>both move</th>
</tr>
</thead>
<tbody>
<tr>
<td>light</td>
<td>c const. w shift</td>
<td>c const. w shift</td>
<td>c const. f shift</td>
</tr>
<tr>
<td>water</td>
<td>v shift</td>
<td>v const. w shift</td>
<td>v shift f shift</td>
</tr>
<tr>
<td>sound</td>
<td>f shift</td>
<td>f shift</td>
<td>f shift</td>
</tr>
</tbody>
</table>

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 79]

• 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.)

3.14 Parallax

• prerequisite: Cosmic Perspective

• 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 80] The parallax angle is half of the shift.

• Consider an arcsecond: \( 1" = 1^\circ/3600. \) What would a dime look like when viewed from a distance of 2 km? [sketch 81] An object can be so far away that its parallax angle is \( 1^\circ; \) it’s distance is \( \pm 3.26 \) 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: \( d = 1/p. \)

• 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.

3.15 Proper Motion & Radial Velocity

• prerequisite: Doppler Shift

• prerequisite: Parallax

• Proper motion can be measured with two images taken one year apart. [sketch 82] (Why must it be one year?) Consider three possible paths of a star that show the same proper motion. [sketch 83] How will we know which is the true space velocity?

• Radial velocity can be measured with Doppler shifted spectral lines. [sketch 84] (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 85]
So we see that if we add the arrows together, we find that proper motion plus radial velocity equals the true space velocity. \[26\]

\[26\] This is just vector addition.
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 Physical Principles

4.1 Special Relativity

- prerequisite: Electromagnetic Radiation
- The principle of relativity (a.k.a. Galilean relativity or Newtonian relativity) is elementary and deals with an observer’s frame of reference. When a quantity depends on an observer’s reference frame, we say it’s relative. If the quantity is independent of an observer’s reference frame, then it’s not relative.

For example, the number of atoms in a ball is not relative; it’s the same whether you stand next to the ball or run past it. On the other hand, the trajectory of a ball through the air is relative. Do the keys go straight up and down as the tosser walks across the room? Or do they follow a parabolic arc? The answer is both, depending on the frame of reference.

If one rolls a ball up a aisle of an airplane in flight, how fast is the ball moving? 5 km/hr or 605 km/hr? The answer is both, depending on your frame of reference. When a supersonic airplane flies from Nairobi, Kenya to Quito, Ecuador, how fast is it going? Zero km/hr or 1670 km/hr? Obviously, velocity is relative.

In relativity, all reference frames are equally correct. After all, why should the surface of the Earth be the only correct reference frame? The Earth spins, and it orbits the Sun. Should the Sun’s reference frame be “correct” when it orbits around the Milky Way? The Milky Way moves toward Andromeda. The entire universe is expanding. Clearly, there can be no single correct reference frame!

- Einstein’s special theory of relativity has two basic postulates. One is that the laws of physics are not relative. The other is that the speed of light (in a vacuum) is not relative. Special relativity is valid for inertial frames of reference. An inertial frame of reference is one without acceleration.

These two postulates seem innocuous, but they have some very surprising implications. Not only is velocity relative, but time, simultaneity, length, and mass are all relative.

Before we embark on our exploration of special relativity, we must become wary of our own common sense and intuition. (For example, as children we might have thought that things fall “down” when dropped. But our common sense had to change when we learned the Earth is round. Our “new” common sense tells us things fall toward the Earth’s core when dropped.) That is, our intuition can easily be wrong. In the case of special relativity, common sense is no good and intuition won’t help; ignore them for the time being.

Consider the “twin paradox”. One test of this effect used synchronized cesium atomic clocks in high-speed airplanes.

The experimental results were in agreement with special relativity.

- Consider Galilean relativity in contrast with special relativity’s second postulate. What does the student measure when the professor throws the baseball at 75 km/hr forward from the top of the train car if the train is stationary relative to the ground? If the train car is moving at 75 km/hr relative to the ground? What of the same questions applied to a light beam from a flashlight instead of a baseball?

- The relativity of time is known as time dilation. Keys tossed into the air do not exhibit time dilation, but a light clock on a very-high-speed train does.

  - Consider again the simple example of tossing keys into the air. What does the student measure if the professor is standing still? The student and the professor get the same results: \( d = 2 \text{ m}, v = v_1, \) and \( t = 1 \text{ s}. \) Why? If the professor is walking, he still gets the same results (why?), but the student gets new results: \( d > 2 \text{ m}, v > v_1, \) but still \( t = 1 \text{ s}. \) Since the two observers agree on \( t, \) they must disagree on \( d \) & \( v, \) because \( d = vt \) (or \( t = d/v).\)

  - In the case of a light clock, things are similar, but different. If the train is not moving, the student and the professor get the same results: \( d = 2h, v = c, \) and \( t = 2h/c. \) If the train is moving, the professor still gets the same results, but the students gets new results: \( d > 2h, v = c, \) and \( t > 2h/c. \) We pretend that the train is going very fast, so the effect is noticeable.) Since the two observers agree on \( v, \) they must disagree on \( d \) & \( t. \) That is, if the student says the event took longer, then amount of time that passed is different for the student and the professor. Who is correct? They are both correct. The rate at which time passes depends on the reference frame: time is relative.

- The relativity of length is called length contraction. When the student on top of the barn sees the professor holding a ladder while standing still, they both agree on the length of the ladder and the length of the barn. A 10 m ladder will not fit in a 5 m barn. Or will it? If the professor could run very fast (so the effect is noticeable), then the student would see the ladder fit inside the barn. This happens because the length of the ladder is relative; the faster the professor runs, the shorter the ladder in the student’s frame of reference. Length contraction occurs only along the direction of motion.

Of course, since everything is relative, the professor would say the ladder did not fit in the barn, because it was the barn that shrunk! Who is correct? Both are correct. The

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28This phenomenon was verified as early as 1938.

29Michelson & Morley showed the world in 1887 that the speed of light is not relative. They did this by showing – accidently – that there is no luminiferous aether.

30Time doesn’t pass in the photon’s reference frame, and so for a photon, all trips take zero time.
length of an object depends on the reference frame; length is relative.\footnote{In the photon’s reference frame, all distance are equal to zero, which is why (in the photon’s frame) no time can pass when it travels.}

Length contraction has been verified by experiment many times over. One of the most popular experiments involves muons\footnote{Like the electron, the muon belongs to the class of particles known as leptons; it’s basically a heavy electron – about 200 times heavier. (A lepton is an elementary subatomic particle; it’s not composed of smaller particles and it’s not made of quarks, which are themselves elementary subatomic particles. A particle made of quarks is classified as a hadron. Hadrons come in two types. Mesons are made of two quarks: a quark-antiquark pair. Baryons are made of three quarks.) The muon was originally named the $\mu$-meson. It was later found not to be a meson at all.} which are created when cosmic rays\footnote{A cosmic ray is usually a very high speed proton produced by a supernova, which is the catastrophic explosion at the end of the life of a very massive star.} enter the Earth’s upper atmosphere. Since muons decay after only a couple microseconds, they should not be able to reach the surface of the Earth. However, since the thickness of the atmosphere is length contracted in the muon’s reference frame, they have no problem traversing the distance to the Earth’s surface, and we therefore detect many of them.

- The relativity of mass is called mass increase. A faster moving object will have more mass than an identical object at rest. This is the reason that no mass in the universe can travel at, or greater than, the speed of light. The speed of light is, therefore, truly the universal speed limit.\footnote{This can be found from the simple formula $m = \gamma m_0$, with which we see that a body travelling at speed $c$ would have infinite mass. But the universe itself isn’t infinitely massive, therefore no mass in the universe can be infinite. Furthermore, a body travelling faster than speed $c$ would need imaginary mass, and speed up as it lost energy. (Recall that the square root of a negative number is an imaginary number. For example $\sqrt{-1} = i$.)}

- What if we pretend that the speed of light is relative? Consider two automobiles colliding in an intersection, with an observer standing down the street. \footnote{Some say light is a particle, but particles don’t interfere with each other; for example, when two baseballs collide in the air, they don’t cancel each other!} The observer would see something that has never been seen before – an absurdity. One car would enter the intersection and stop when it crashed into nothing. Later, the other car would enter the intersection and crash into the car already there. So there are only two possibilities. Either $c$ is constant and $t$ is relative, or $c$ is relative, $t$ is not relative, and cars can crash into nothing. Einstein chose the former, and he was correct!

- Reading.
  - TCPF2: Chapter 10, Section 2, page 173, SR (not GR).

- Homework.

1. (5 points) Consider the example of Galilean relativity in which the professor throws the baseball. Let’s modify the example such that the professor throws the baseball at 90 km/hr backward from the top of the train while the train is moving forward at 150 km/hr relative to the ground. What is the speed of the ball as measured by the professor? What is the speed of the ball as measured by the student? Justify your answers.

2. (5 points) Consider the example of the professor tossing keys into the air. Now imagine the professor makes the same toss as he walks forward at speed $s$, walking on a train that is stationary relative to the ground. Suddenly, while the keys are still in the air, the train starts moving and subsequently moves backward at speed $s$. As the train moves at this speed, what will be the motion of the keys as observed by the student standing on the ground? As observed by the professor? Justify your answers.

3. (5 points) Consider the example of the professor with a ladder running through a barn; the student saw the ladder fit in the barn while the professor did not. Now imagine that the professor is standing still on the ground, but the barn, with the student sitting on top, is on wheels and moving at very high speed toward the professor. Will someone see the ladder fit in the barn? If so, will it be the student or the professor? Justify your answers.

4.2 Duality Of Light

- prerequisite: Electromagnetic Radiation in Brief

- Interferometry is the measurement of interference, which is the overlap of waves. Consider water waves passing through each other.

First think of two travelling crests in three stages: toward, overlapping, & away from each other. \footnote{The phenomenon of diffraction is another example of irrefutable evidence that light is a wave, and it can’t be a particle.} Where the waves overlap, the amplitude is “double positive”. Next, think of two waves, each with a crest and a trough, in five stages: toward, initial overlap, full overlap, final overlap, & away from each other. \footnote{The word pixel is short for “picture element”.} Where the crests overlap, the amplitude is “double positive”. Where the troughs overlap, the amplitude is “double negative”. Where a crest overlaps with a trough, the amplitude is zero.

Finally, think of two sets of interfering, circular water waves – like the result of simultaneously dropping two rocks near each other into a smooth pond. \footnote{When light waves strike the CCD, all pixels should detect the signal at the same time.} Consider several locations each of double positive amplitude ($\bullet$), double negative amplitude ($\times$), and zero amplitude ($\circ$).

We find a similar situation with two radio transmission dishes with interfering, semi-circular radio waves. Again, consider locations: $\bullet$, $\times$, and $\circ$. \footnote{Each pixel is an individual light detector.} [sketch 99]

When light waves strike the CCD, all pixels should detect the signal at the same time. \footnote{If this is not convincing, consider a line of people on the shore with parallel water waves approaching. Note that each person in the line would need twice as many people to see a wave.} [sketch 100]

- Interferometry shows us, beyond any doubt, that light must be a wave. Some say light is a particle, but particles don’t interfere with each other; for example, when two baseballs collide in the air, they don’t cancel each other!

- But something else is happening. Consider a digital camera, which uses a CCD (charge-coupled device) instead of film. A CCD has millions of tiny little squares; each is called a pixel. Each pixel is an individual light detector. [sketch 99]
will experience the wave’s arrival at the same time. [sketch 101] But this is not what happens! Rather, individual particles of light strike pixels one at a time. [sketch 102] A particle of light is called a photon.

- CCD’s show us, beyond any doubt, that light must be a particle. Some say light is a wave, but waves can’t strike individual pixels one at a time!

- This should seem a bit confusing. On one hand we find that light is a wave; it can’t be a particle. On the other hand we find that light is a particle; it can’t be a wave. The only possible conclusion is that light is a particle and a wave and neither.

When an experiment is performed that will work only if light is a wave and that will fail if light is a particle, it works. But when an experiment is performed that will work only if light is a particle and that will fail if light is a wave, it works. Again, the only possible conclusion is that 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.

- Homework.

1. (5 points) Consider the three-stage and five-stage examples of interference, and imagine combining the two: a single crest approaching a wave with a crest and a trough. How many stages are appropriate in this example? Is there a stage with zero amplitude? If so, which one? Sketch these stages.

4.3 Uncertainty Principle

- prerequisite: Newton’s Universal Law of Gravitation
- prerequisite: Quanta, Absorption, & Emission
- Before considering W. Heisenberg’s uncertainty principle, we will explore the philosophical context: determinism vs. free will. Is there such a thing as fate or destiny?

   Here we proceed with a point of view based on what was known about forces in physics at the end of the 19th century. Let’s consider Newton’s 2nd law of motion \( F = ma \), along with Newton’s universal law of gravitation \( F = \frac{GMm}{d^2} \), for our Sun plus the eight planets.

   Each of the nine bodies obeys \( F = ma \); that is, the acceleration of a body depends on the forces acting upon it. What forces are acting on each body? The answer is the gravitational forces due to the other eight bodies. For example, there are eight forces acting on the Earth; these are the gravitational forces due to \( \odot, \oplus, \bigcirc, \delta, \gamma, \beta, \psi \). So each of the nine bodies feels eight forces; therefore, there are 72 forces. Do we need 72 equations? No, we only need 36 because, for example, the gravitational force on the Earth due to the Sun is equal to the gravitational force on the Sun due to the Earth.

   So we calculate 36 forces and use them to find nine accelerations – one acceleration for each body. But then, of course, after each body accelerates, the distances have all changed between the bodies, and therefore so have all the gravitational forces. In other words, we can calculate the results of 45 equations, but the results are only valid for a brief moment in time. After that moment has passed, we must recalculate all 45 equations. Obviously, though it can be done by hand, it’s best done using a computer.

   Using such calculations, astronomers today can predict planet locations 3000 years in the future! And using similar calculations, astronomers today can predict eclipses (exactly when and where) 1000 years in the future. [sketch 103] But what if there were no computers? What if we couldn’t predict eclipses? Would the eclipses still occur on time? Yes, of course they would. And if we couldn’t predict the planet locations, they too would occur on time. In other words, these events are destined to happen whether or not we are capable of predicting them.

   Now let’s consider a system far more complicated than the 9-body system we just analyzed. Let’s consider every proton, neutron, and electron in the universe; each exerts forces on all of the others. Here, the interactions are more complicated – even though we can ignore the gravitational forces between the particles – because we must take into account electric forces and magnetic forces. Nonetheless, the laws for these forces exist and all particles in the universe obey them. If we were smarter and we had unlimited computing power, we could make all the necessary calculations and figure out where all the particles in the universe would be in the distant future.

   As it turns out, we can’t make the necessary calculations. But as it is for eclipses and planet locations, the particles in the universe will still obey their deterministic laws. At some point in the future, 1000 years let’s say, all of the protons, neutrons, and electrons in the universe will be in there predestined positions. What does this really mean?

   * Consider your thoughts and feelings. What are they? They are configurations of cells and nerve impulses in your brain. But those cells and

\[ \text{The photoelectric effect is another example of irrefutable evidence that light is a particle, and it can't be a wave.} \]

\[ \text{Young's interference experiment is a wonderful example of this. For a truly great presentation of this by the famous Prof. Richard P. Feynman, see one of the Messenger Lectures at Cornell University in 1964. Choose Lecture 6: Probability and Uncertainty – The Quantum Mechanical View of Nature. To find it, google Project Tua.} \]

\[ \text{All these years this amazing object, light, has been all around you; did you ever stop to consider its true nature?} \]

\[ \text{We will keep our consideration simple by ignoring dwarf planets, moons, asteroids, comets, and other TNO's.} \]

\[ \text{That is,} \quad F_{\odot} = \frac{GM_{\odot}m_{\oplus}}{d_{\odot}^2} = \frac{GM_{\odot}m_{\bigcirc}}{d_{\odot}^2} = \frac{GM_{\odot}m_{\delta}}{d_{\odot}^2} = F_{\odot}. \]

\[ \text{We can do this because the gravitational force between two subatomic particles is typically about} \times 10^{42} \text{times weaker than the electric force between the same two particles!} \]

\[ \text{It's impossible to use a computer to model every particle in the universe at once, because at least one magnetic hard drive particle – which is larger than a p+ or anything – is needed for each piece of information. If the number of required magnetic hard drive particles equaled the number of particles in the universe, then such a hard drive would far outweigh the universe itself and so could never be built.} \]
nerve impulses are constructed from protons, neutrons, and electrons. Therefore, your thoughts and feelings are governed by the same deterministic force laws that govern these subatomic particles. In other words, you have no control over your thoughts, feelings, and actions. You are a chemical machine, and everything you do obeys the force laws between subatomic particles.

What are you going to have to lunch tomorrow? Is it up to you? As it turns out, it’s not. What you have for lunch tomorrow has been predetermined—it is your destiny!—since the universe began 13.8 billion years ago. Since then, all the protons, neutrons, and electrons in the universe, including those that make up your brain, have been doing the only thing they can; they have been obeying the force laws that govern their behavior.

Once the initial state of a system occurs, all future states of the system are fated, destined, predetermined. Our system is the universe, and there is no such thing as free will.

Now we may place the uncertainty principle in such a context. The uncertainty principle tells us that no physical quantity can be known exactly, because no physical system has an exact state.

The universe obeys the uncertainty principle, and therefore it cannot be deterministic. In reality, there is no fate, no destiny, and no determinism!

The position-momentum form of the uncertainty principle is expressed as \( \Delta x \Delta p \geq \frac{\hbar}{2\pi} \). Here, \( \Delta \) represents the uncertainty in the measurement of a quantity (such as position or momentum), \( x \) is the position of the particle, \( p \) is the momentum of the particle, and \( \hbar \) is actually \( \frac{\hbar}{2\pi} \), where \( \hbar \) is Planck’s constant, which is a very, very small number.

What does the uncertainty principle tell us?

Consider a simple question. How do you know the door to the room is still in place? You don’t feel, hear, or smell it. You know it’s there because you see it. This means that you locate it by receiving photons that have bounced off of it. The same must be true for an electron; if you try to locate it, you must bounce a photon off of it. But photons and electrons have similar energies, so their interactions can resemble those between billiard balls. [sketches 104 & 105]

We might say something about where the electron was when the photon bounced. Of course, we could decrease our \( \Delta p \) by using a low energy photon. But then, since the low energy photon has a long wavelength, we would be increasing \( \Delta x \). In other words, \( \Delta x \) and \( \Delta p \) are inversely proportional; as one decreases the other increases, and conversely. And we can readily see this in the equation above. The product of the two uncertainties can never be zero.

The energy-time form of the uncertainty principle is expressed as \( \Delta E \Delta \tau \geq \hbar \). Here, \( E \) is the energy of the particle, and \( \Delta \tau \) is the duration of time during which the measurement of energy takes place.

Consider two light waves, with very similar wavelengths. [sketch 106] We see that if \( \Delta \tau \) is small, then it’s difficult to tell if the two waves have the same wavelength or not—we are uncertain about the wavelengths. Since \( E = \frac{hc}{\lambda} \), the uncertainty about \( \lambda \) means we must be uncertain about \( E \); and so \( \Delta E \) is large. On the other hand, we could minimize \( \Delta E \) by observing for a longer duration, but this would necessarily increase \( \Delta \tau \)! Again, we can readily see this inverse proportionality in the equation above. And again, the product of the two uncertainties can never be zero.

We see that the uncertainty principle is not a issue of technology. No matter how advanced we become, we will always have the same problems with locating electrons and measuring photons. But the uncertainty principle tells us things about the nature of the universe that are much deeper and more profound than what we’ve explored so far. The underlying reason why no exact measurements can be made is because the electron doesn’t actually have an exact position, nor does the photon actually have an exact wavelength.

Why is the nucleus of an atom so much smaller than the atom itself? In other words, if the proton is much more massive than the electron, then shouldn’t it be much bigger? The answer comes from the uncertainty principle. Neither the proton nor the electron actually have any size. They are really just clouds of uncertainty. When we speak of the size of the nucleus and the size of the atom, we are actually referring to the size of the proton’s uncertainty in position and the size of the electron’s uncertainty in position, respectively. Generally, the uncertainty in position of a particle is inversely proportional to the mass of the particle. So the electron’s cloud is about 2,000 times bigger that the proton’s.

Do you really think you could force one of the electrons in your brain to be repelled by, instead of attracted to, one of the protons in your brain?

Momentum is the product of mass and velocity: \( p = mv \).

It turns out that \( h/2\pi \) can appear more frequently in the equations of quantum mechanics than does \( h \) by itself. It is for this reason that the symbol \( \hbar \) was created.

\( \hbar \)’s value is \( 6.626 \times 10^{-34} \) J-s.

Planck’s constant appeared earlier, in the formula for the energy of a photon: \( E = \frac{hc}{\lambda} \).

Remember that \( E = hf \) and \( c = \lambda f \); so we have \( E = hc/\lambda \).

This works because the position of any object cannot be known with an accuracy better than the wavelength of the light being used. In other words, one cannot resolve an object smaller than the wavelength used to observe it.

More precisely, they are clouds of probability – more detail on this in the section about quantum states.

\[ \Delta x \Delta p \geq \frac{\hbar}{2\pi} \]

\[ \Delta E \Delta \tau \geq \hbar \]
cloud; in other words, the atom is about 2,000 times bigger than the nucleus inside it.\[^{55}\]

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

• Homework.
  1. (6 points) Consider the example of forces between nine bodies and their accelerations; we had 45 equations to calculate and recalculate over and over again. Imagine there were only six planets in the solar system. How many forces would there be? How many force equations would be needed? How many accelerations would there be? How many equations would we have to calculate and recalculate over and over again? Justify your answers.

4.4 Quantum States

• prerequisite: Special Relativity

• prerequisite: Duality of Light

• prerequisite: Uncertainty Principle

• A quantum state can be thought of as an attempt to describe a quantum system (e.g., an atom). Our basic approach to the concept of quantum states will be to understand a three-dimensional Gaussian probability distribution, which is somewhat like the behavior of an electron in a hydrogen atom when it’s in the ground state, or when it’s in a superposition of states\[^{56}\] which means the electron is in the ground state \(\text{and all of the excited states \& none of them} \text{ – all at once.}

  – In 1-D, a Gaussian function (named after C. F. Gauss) has the form \(y \propto e^{-x^2}\)\[^{57}\] This function is a.k.a. the “bell curve”\[^{58}\]

    * Consider examples. We could plot number of people vs. IQ\[^{59}\] or we could plot number of people vs. test scores in a class. If the distribution is “normal”, we find the result is a Gaussian function. \([\text{sketch 107}]\)

\[^{55}\] Briefly, \((\Delta x_{-}/\Delta x_{+} \sim (m_{p+}/m_{-}) \sim 2,000.\)

\[^{56}\] Any quantum system can be in a superposition of states or in an eigenstate. Given a quantum system, laboratory experiments can be performed to measure special quantities called observables. When such a measurement is made, the quantum system will be in a special quantum state known as an eigenstate. This resulting eigenstate can be one of many possible eigenstates, but it’s impossible to predict which one before the measurement is made; only the relative probabilities can be predicted. Before such a measurement is made, the system will be in a combination of eigenstates known as a superposition of states. After the measurement is made, the quantum system will evolve in a deterministic way.

\[^{57}\] The number \(e \approx 2.718281828\) (not to be confused with the electronic charge, \(e\)) is known as Euler’s constant and is the base of the natural (or Naperian) logarithm. It is a very special number for several reasons, one of which is it’s the only number for which \(\frac{d}{dx} e^x = e^x\) (which means if you could live on this exponential curve, you would have no way of telling where you are on that curve).

\[^{58}\] This is the notion underlying grades based on a curve.

\[^{59}\] This is the “intelligence quotient”. Of course, a quotient is a ratio between two numbers. In this case, the ratio is “mental age” divided by physical age.

In 2-D, a Gaussian looks more like a hill. \([\text{sketch 109}]\) Notice that it has the same property as the 1-D Gaussian: the value of the function decreases as the distance from the middle increases.

A 3-D Gaussian is nearly impossible to draw. \([\text{sketch 110}]\) It’s like a spherical cloud in which the density decreases with distance from the cloud’s core. Imagine flying in an airplane through such a cloud; what would it look like?

  – The mathematical probability of an event is always \(0 \leq P \leq 1\). In physics, we usually have to say \(0 < P < 1\). For example, what is the probability that a fair coin toss will show tails? Heads? \((P = .5)\) What is the probability that two fair coin tosses will show two tails? \((P = .25)\)

A probability distribution is the answer to the question of what is the probability for each and every possible outcome of an event. For example, what is the probability that someone will be \(h\) meters tall and have an IQ of \(n\)? \([\text{sketch 111}]\)

What is the probability that someone will be \(h\) meters tall, with an IQ of \(n\), and weigh \(W\) pounds? \([\text{sketch 112}]\) This is a 3-D Gaussian probability distribution.

• What is the probability that an electron will be located in space at position \((x, y, z)\)? \([\text{sketch 114}]\) An electron doesn’t have an actual position. It’s better to say the electron is its quantum state: no more, no less.\[^{60}\] This fits very well with the uncertainty principle, wherein \(\Delta x\) is directly related to the width of the Gaussian. \([\text{sketch 115}]\)

How does an electron behave? What would a human look like if he or she could behave like an electron?\[^{61}\]

An atom doesn’t really look anything like the Bohr model that we’ve discussed. \((\text{Recall the section Quanta, Absorption, \& Emission.})\) \([\text{sketch 116}]\) A much more accurate drawing of an atom is even simpler. \([\text{sketch 117}]\)

• A well-known phrase in quantum mechanics is collapse of the wave function. This is related to what happens to a quantum state upon measurement of an observable such as the electron’s energy in an atom. It can seem like the quantum state changes instantaneously from a superposition of states to an eigenstate such as the ground state. However, another way of looking at this is that there is no collapse at all; that is, the quantum state of the atom becomes entangled with the quantum state of the measuring apparatus.\[^{62}\] And when the measurement is recorded in the laboratory, the entangled state of the atom plus apparatus becomes entangled with the scientist (and so on).

• Interpretation of the quantum state is important in physics and has intriguing philosophical implications. Consider the old debate regarding the EPR paradox. This paper was written in 1935 by Einstein, Podolsky, & Rosen. It suggested that if the theory of quantum mechanics is to avoid conflict

\[^{60}\] A more accurate version of this concept includes the fact that the quantum state is complex, which means it has both real and imaginary parts. Yet, the probability that a measurement will result in some value is real (it has no imaginary part) and is related mathematically to the quantum state.

\[^{61}\] This is why Mr. Tomkins needed quantum bullets to hunt quantum elephants (G. Gamow).

\[^{62}\] Entanglement is fundamental in quantum mechanics.
with special relativity (since instantaneous propagation is faster than c), then it must be an incomplete theory. The debate went back and forth, and in the end Einstein admitted that the theory of quantum mechanics does not require the existence of an objective reality; however, he noted that neither did it specifically preclude the existence of objective reality! Yet, in 1964, J. S. Bell wrote a paper showing that quantum mechanics does indeed preclude the existence of objective reality! And Bell’s theorem was experimentally verified in the 1980’s by A. Aspect.

• Homework.

1. (5 points) If we considered a random sample of 100 people, and plotted their weight vs. height, would the curve be like a Gaussian? Justify your answer.

4.5 Exclusion Principle

• prerequisite: Quantum States

• In 1925, W. Pauli stated his exclusion principle. “In a multi-electron atom there can never be more than one electron in the same quantum state.”

• Electrons can be “identical particles”, but in He, two electrons fit in the ground state. How? Consider “quantum numbers”.

There is more than one scheme for quantum numbers, but here we consider only one, in which there are four quantum numbers: n, ℓ, ml, & ms.

– The number n = 1, 2, 3, ... is the principle quantum number and is related to the energy of the particle.

– The number ℓ = 0, 1, 2, ...(n−1) is related to the angular momentum of the particle. [sketch 118] If n = 3, what are the possible values of ℓ?

– The number ml = 0, ±1, ±2,..., ±ℓ is related to the “vertical component” of the angular momentum. [sketch 119] If ℓ = 3, what are the possible values of ml? If n = 3, what are the possible values of ml?

– The number ms = ±1/2 is related to the spin of the particle.

All four numbers together describe the “quantum state” of the particle. [sketch 120, 121, & 122]

Consider “upside-down quantum numbers trees”. [sketches 120, 121, & 122]

• The exclusion principle applies to fermions; it does not apply to bosons. A fermion is any particle (atomic, subatomic, or other) that has “half-integer spin”: that is: ±1/2, ±3/2, ±5/2, and so on. Examples are electrons, protons, and neutrons. A boson is any particle (atomic, subatomic, or other) that has “integer spin”: that is: 0, ±1, ±2, ±3, and so on. Examples are photons and 1H atoms. Is 7Li° a boson or fermion?

64The verification is not absolute; there may be some “loopholes” in the experiments.

65Classically, angular momentum is given by \( \mathbf{L} = \mathbf{r} \times \mathbf{p} \) or \( L = mvr \). In quantum physics, it’s similar but different.

A 4He atom is a boson, but a 3He atom is a fermion. (Why?) In He, the two electrons have the same energy, angular momentum, and vertical component of angular momentum, but they have different spins. Why can’t three electrons fit in the ground state? The answer is because the probability is zero (\( P = 0 \)) for a fermion to be found where two identical quantum states overlap. [sketches 123 & 124]

• An element’s chemical properties (how it interacts with others) are determined by its location in the periodic table, but it’s location in the table is determined by the exclusion principle. That is, all of chemistry is a result of Pauli’s exclusion principle.

• Reading.

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

• Homework.

1. (3 points) Assume \( m_e = -4 \). What values of n are allowed? What values of n are not allowed?

2. (5 points) Use the “upside-down quantum numbers trees” to explain how the Pauli Exclusion Principle determines the shape of the top two rows of the Periodic Table of the Elements. Remember that the exclusion principle applies to fermions, not bosons.

3. (4 points) Is 56Fe° a fermion or boson? What about 195Pt°? Justify your answers.

4.6 Matter & Antimatter

• prerequisite: Quanta, Absorption, & Emission

• prerequisite: Magnetic Fields

• The name antimatter seems to imply that it is another form of mass – something other than regular mass. But this is misleading. There is no difference between matter and antimatter other than charge. (Recall that opposite charges attract, and like charges repel.)

The most common example of antimatter is the positron, which is just like an electron, except its charge is positive. Here we compare a few matter and antimatter particles. [sketches 126 & 127]

<table>
<thead>
<tr>
<th>particle</th>
<th>mass</th>
<th>charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron</td>
<td>( m_e )</td>
<td>(-e)</td>
</tr>
<tr>
<td>proton</td>
<td>( m_p )</td>
<td>(+e)</td>
</tr>
<tr>
<td>positron</td>
<td>( m_e )</td>
<td>(+e)</td>
</tr>
<tr>
<td>antiproton</td>
<td>( m_p )</td>
<td>(-e)</td>
</tr>
</tbody>
</table>

Why is the universe made of matter instead of antimatter? One answer is that if the universe were made of antimatter, we would have named that matter, and vice versa. Also, we’ll consider symmetry breaking later in the course, in the section Early Universe.

• Though it’s possible to form antihydrogen [sketch 125], usually matter and antimatter annihilate each other in a collision when they meet. Consider pair annihilation and pair production. [sketches 126 & 127] Note that \( E = mc^2 \) leads to \( m = E/c^2 \).

66Note that \( m_e \approx 9.11 \times 10^{-31} \text{ kg} \), \( m_p \approx 1.67 \times 10^{-27} \text{ kg} \), and \( e \approx 1.6 \times 10^{-19} \text{ C} \) (not to be confused with Euler’s constant, \( e \)).
• If we ignore the extremely complicated details of the quarks and gluons (and their virtual counterparts), we can state simply the distinction between a proton and an antiproton. A proton is made of two ups and one down, while an antiproton is made of two antius and one antidown. Likewise, a neutron is made of one up and two downs, while an antineutron is made of one antuit and two antidowns.

• How do we know about quarks and antiquarks? The answer is the particle accelerator, along with its detectors. Consider the interaction of charged particles with magnetic fields. (Recall the section Magnetic Fields.) [sketch 128]

Let’s look at this interaction more closely. First we must learn a little about vectors and how they can be multiplied together.

– A vector is like a number (with units) with direction; it has two quantities. Examples are velocity (1. speed, 2. direction), force (1. strength, 2. direction), and momentum (1. mass times speed, 2. direction). In constrast, a scalar is just a number (with units). It’s what we all so familiar with. Examples include weight, speed, mass, and length.

– Since a vector has two quantities, there are two types of multiplication: the dot product and the cross product. We consider here the cross product, which uses a form of the right-hand rule. Consider a 3-D coordinate system. We represent the axes with vectors: \( \mathbf{x}, \mathbf{y}, \text{&} \mathbf{z} \). [sketch 129] We note that \( \mathbf{x} \times \mathbf{y} = \mathbf{z} \) and \( \mathbf{y} \times \mathbf{x} = -\mathbf{z} \). (We find that \( \mathbf{x} \times \mathbf{y} \neq \mathbf{y} \times \mathbf{x} \), and the commutative law of multiplication is not obeyed!)

Now we consider the effect of a magnetic field on a moving charged particle: \( \mathbf{F} = q\mathbf{v} \times \mathbf{B} \). Here, \( \mathbf{F} \) is the magnetic force on the particle, \( q \) is the particle’s charge, \( \mathbf{v} \) is the particle’s velocity, and of course \( \mathbf{B} \) is the magnetic field.

Consider several examples. So we see the direction of the particle’s deviation from a straight line tells us if the charge is positive or negative, and the tightness of the spiral tells us something about the “magnitude” of the particle’s charge, as well as its mass.

• Reading.

– TCPF2: Chapter 13, Section 1, pages 214 - 215.

• Homework.

1. (3 points) Imagine a proton collided with an antiproton and energy was released as \( \gamma \)-rays. Would you expect this total energy to be greater than, equal to, or less than the total energy of the \( \gamma \)-rays released during pair annihilation? Justify your answer.

2. (4 points) A proton is traveling due north along the surface of the \( \odot \). As it crosses the equator, you suddenly turn on a strong \( \mathbf{B} \) that runs vertically, from the ground to the sky. What is the new motion of the proton? Explain.

4.7 Arrow of Time

• Why does time go only one way? The answer is only because it’s more likely to go forward than backward. That is, it can go backward; it just doesn’t do so.

The 2nd law of thermodynamics is about entropy, which is sort of a measure of disorder. The 2nd law implies a flow from order to disorder. This flow is identical to the arrow of time.

Can disorder flow toward order? Can the 2nd law be violated? Can entropy decrease? The answer to all three of these questions is yes. However, do any of these three events happen in a closed system? The answer is no.

– A closed system is one that suffers no influence from outside. The Earth is not a closed system, mainly because of the Sun’s influence. The only truly closed system in the universe is the universe itself.

– There are many situations in which entropy decreases. For example, consider the degree of order in the atoms of our brains. Years before we were born, our “brain atoms” were scattered around the Earth: a very disordered state. So the growth of a brain represents a dramatic increase in order and a dramatic decrease in entropy.

However, the brain is not a closed system; it never was. During the growth of a brain, many nutrients are digested and processed by the body. The digestion and processing generate heat — a lot of heat. In fact, the amount of disorder associated with this heat is far greater than the amount of order associated with the construction of a brain. So we see that the closed system is the brain plus the heat. And in this closed system, the overall entropy has increased.

• How many arrangements are there for eight people to sit at a table? Think about it. The first of eight to sit has eight chairs from which to choose: eight possible arrangements. The second to sit has seven chairs from which to choose: seven possible arrangements for each of the original eight possibilities. So there are 56 possible arrangements for two people among eight chairs. The third to sit has six chairs from which to choose, leading to 336 possibilities for three people. And so on for the rest of the people. The answer is \( 8! = 40,000 \). (Here we note that 8! is read as “eight factorial” and means \( 8 \cdot 7 \cdot 6 \cdot 5 \cdot 4 \cdot 3 \cdot 2 \cdot 1 \))

• Consider a deck of 52 cards, perfectly ordered when purchased. When we shuffle the deck, it becomes disordered. Every time we shuffle the deck, the result is a disordered state. So there is one ordered state that is possible, and all of the other possible states are disordered.

\(^{67}\)The theory of quantum chromodynamics is exceedingly complicated. It describes the interactions between quarks, gluons, virtual quarks, and virtual gluons. No one has yet even been able to understand QCD well enough to find the answer to the question of why a proton has a spin of one half.

\(^{68}\)A quark is a subatomic particle that comes in six flavors: up, down, charm, strange, top, & bottom.

\(^{69}\)A gluon is a particle that carries the strong nuclear force.

\(^{70}\)Hence a proton has positive charge while a neutron has none.

\(^{71}\)This is the reason why you’ve seen dots and crosses used for multiplication, such as \( a \cdot b \) and \( a \times b \). With vectors, these symbols don’t have the same meaning; that is, \( \vec{a} \cdot \vec{b} \neq \vec{a} \times \vec{b} \).
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\(^{76}\) (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.

5.2 Space Exploration: Past & Present

- Newton’s Universal Law of Gravitation
- Sputnik 1 (“companion”) was launched on 1957 October 04 by the Soviet Union. It weighed 184 lbs, and was the size of a basketball. Its orbital period was about 98 minutes.
  - Sputnik 2 was also launched in 1957 and carried Laika, the dog, who lived for several hours.\(^{77}\)
  - There are other noteworthy events\(^{77}\)
    - On 1961 April 12, Yuri Gagarin became the first man in space\(^{78}\) (What is an orbit? [sketch 130] What does a cosmonaut, or an astronaut, feel?)
    - On 1969 July 20, the Apollo 11 mission landed men on the moon\(^{79}\)
    - Many craft have flown through parts of our solar system, and many are still headed to their destination. Some highlights are found in the table.

5 Solar System

5.1 Overview of Solar System Objects

- prerequisite: Cosmic Perspective
- Our discussion of planets\(^{74}\) 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.”
  - But consider the trend...
    - \(8! \approx 10^4\)
    - \(52! \approx 10^{68}\)
    - \(10^{86}! \approx 10^{10^{71}}\)
- Given the nature of the uncertainty principle and how it governs the behavior of atoms, we admit the possibility that an atom should be able, if just for the briefest moment, to move back to where it was the instant before. The odds of this are not great, but it’s not impossible. So what are the odds that every atom in the universe would do this at the same moment? The chance is so exceedingly small that we can safely say that it won’t happen.
  - However, even if the odds of this happening are far less than 1 in \(10^{86}\), the bottom line is that the odds are not zero. So there is a chance it can happen. If this happened, what would it mean? Think about it. Is there any better definition for time going backward than that of every atom in the universe going back to where it was the instant before?
  - So is it possible for time to go backward? Yes. Does it happen? No. Why not? Because time is at least \(10^{86}\) times more likely to go forward than backward! Hence, the “arrow of time”.\(^{20}\)

\(^{72}\)If all 7 billion people on Earth could shuffle a trillion times every second, and we did this for a trillion times the age of the universe, it would not be enough. We would have to repeat this scenario a hundred thousand trillion times before we had a chance at getting a single ordered deck!
\(^{73}\)WU 170 1-1, 1-2, 1-3 (35’)
\(^{74}\)WSS 100 2-1 (8’)

\(^{75}\)Ceres, Pluto, Haumea, MakeMake, Eris, and maybe Sedna.
\(^{76}\)A dwarf planet must meet three criteria. First, it must orbit a star, as opposed to a planet or a dwarf planet. Second, it must be massive enough to be spherical, so that it may overcome compressive strength and achieve hydrostatic equilibrium. Third, it must not be massive enough to clear its orbit of planetessimals – by collision, capture, gravitational disturbance, or establishment of orbital resonances that prevent collisions.
\(^{77}\)http://www.youtube.com/watch?v=8OtYwzWQf9Q
\(^{78}\)http://www.youtube.com/watch?v=8OtYwzWQf9Q
\(^{79}\)http://www.youtube.com/watch?v=8OtYwzWQf9Q
\(^{80}\)As of 2011, current missions included Cassini, Chandra, Chang’e 2, Dawn, Fermi, Hubble, Kepler, LRO, Mars Express, Messenger, MRO, New Horizons, Opportunity, Planck, Rosetta, SDO, SOHO, Spitzer, STEREO, Swift, Venus Express, and WISE. Also, see wikipedia: space exploration.
<table>
<thead>
<tr>
<th>Planetary Bodies</th>
<th>Mission</th>
<th>Year</th>
<th>Agency</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>☉</td>
<td>Mariner 10</td>
<td>1974-5</td>
<td>NASA</td>
<td>flybys</td>
</tr>
<tr>
<td></td>
<td>Messenger</td>
<td>2008-9</td>
<td>NASA</td>
<td>flybys, will become orbiter</td>
</tr>
<tr>
<td>☉</td>
<td>Venera 3</td>
<td></td>
<td>USSR</td>
<td>crash land</td>
</tr>
<tr>
<td></td>
<td>Mariner 2</td>
<td></td>
<td>NASA</td>
<td>flyby</td>
</tr>
<tr>
<td></td>
<td>more Veneras</td>
<td></td>
<td>USSR</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pioneer Venus</td>
<td>1980’s</td>
<td>NASA</td>
<td>lander</td>
</tr>
<tr>
<td></td>
<td>Vega</td>
<td></td>
<td>int.</td>
<td>headed to Comet Halley</td>
</tr>
<tr>
<td></td>
<td>Magellan</td>
<td>1990-94</td>
<td>NASA</td>
<td>orbiter</td>
</tr>
<tr>
<td></td>
<td>Venus Express</td>
<td></td>
<td>ESA</td>
<td></td>
</tr>
<tr>
<td>☉</td>
<td>Mariner 4</td>
<td>1965</td>
<td>NASA</td>
<td>flyby</td>
</tr>
<tr>
<td></td>
<td>more Mariners</td>
<td></td>
<td>NASA</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mariner 9</td>
<td>1971</td>
<td>NASA</td>
<td>orbiter</td>
</tr>
<tr>
<td></td>
<td>Mars 2 &amp; 3</td>
<td>1971</td>
<td>NASA</td>
<td>crash land, land</td>
</tr>
<tr>
<td></td>
<td>Viking 1 &amp; 2</td>
<td>1975-6</td>
<td>NASA</td>
<td>landers</td>
</tr>
<tr>
<td></td>
<td>MER-A (Spirit)</td>
<td>2003-4</td>
<td>NASA</td>
<td>rover</td>
</tr>
<tr>
<td></td>
<td>MER-B (Opportunity)</td>
<td>2003-4</td>
<td>NASA</td>
<td>rover</td>
</tr>
<tr>
<td>☉</td>
<td>Galileo</td>
<td>1991-3</td>
<td>NASA</td>
<td>flybys: 951 Gaspra, 243 Ida</td>
</tr>
<tr>
<td></td>
<td>NEAR-Shoemaker</td>
<td>2000-1</td>
<td>NASA</td>
<td>orbiter, lander: Eros</td>
</tr>
<tr>
<td>☉</td>
<td>Pioneer 10 &amp; 11</td>
<td>1973-5</td>
<td>NASA</td>
<td>flybys</td>
</tr>
<tr>
<td></td>
<td>Voyager 1 &amp; 2</td>
<td>early 1980’s</td>
<td>NASA</td>
<td>flybys</td>
</tr>
<tr>
<td></td>
<td>Galileo</td>
<td>1995-2003</td>
<td>NASA</td>
<td>orbiter</td>
</tr>
<tr>
<td>☉</td>
<td>Pioneer 11</td>
<td>1979</td>
<td>NASA</td>
<td>flyby</td>
</tr>
<tr>
<td></td>
<td>Voyager 1 &amp; 2</td>
<td>early 1980’s</td>
<td>NASA</td>
<td>flybys</td>
</tr>
<tr>
<td></td>
<td>Cassini</td>
<td>2004-present</td>
<td>NASA</td>
<td>orbiter</td>
</tr>
<tr>
<td>☉</td>
<td>Voyager 2</td>
<td>1986</td>
<td>NASA</td>
<td>flyby</td>
</tr>
<tr>
<td>☉</td>
<td>Voyager 2</td>
<td>1989</td>
<td>NASA</td>
<td>flyby</td>
</tr>
<tr>
<td>☉</td>
<td>Ceres</td>
<td>2015</td>
<td>NASA</td>
<td>flyby, orbiter (launch: 2007)</td>
</tr>
<tr>
<td>☉</td>
<td>21/P Giacobini-Zinner</td>
<td>1985</td>
<td>NASA</td>
<td>flyby</td>
</tr>
<tr>
<td></td>
<td>Int. Cometary Expl.</td>
<td></td>
<td>ESA</td>
<td>flyby</td>
</tr>
<tr>
<td></td>
<td>Halley</td>
<td>1986</td>
<td>ESA</td>
<td>flyby</td>
</tr>
<tr>
<td></td>
<td>Vega 1 &amp; 2</td>
<td>1986</td>
<td>USSR/Fr.</td>
<td>flybys</td>
</tr>
<tr>
<td></td>
<td>Suisei</td>
<td>1986</td>
<td>ISAS</td>
<td>flyby</td>
</tr>
<tr>
<td></td>
<td>Sakigake</td>
<td>1986</td>
<td>ISAS</td>
<td>flyby</td>
</tr>
<tr>
<td>☉</td>
<td>9/P Tempel</td>
<td>Deep Impact</td>
<td>2005</td>
<td>NASA</td>
</tr>
<tr>
<td></td>
<td>Wild 2</td>
<td>2006</td>
<td>NASA</td>
<td>returned with samples!</td>
</tr>
</tbody>
</table>
5.3 Aurora Borealis

- prerequisite: Collisional vs. Radiative Processes
- prerequisite: Magnetic Fields
- 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 131]

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.81

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.

5.4 Introduction to Terrestrial Planets & ⚪

- prerequisite: Cosmic Perspective
- prerequisite: Days & Months
- prerequisite: Kepler’s Laws of Planetary Motion
- prerequisite: Newton’s Universal Law of Gravitation
- prerequisite: Magnetic Fields
- prerequisite: Doppler Shift

81APoD; image search “aurora”; WSS 100 1-4 (14’) (33’40”=12’05”); Dance of the Spirits by Alister Chapman, from 2012 January 24.
5.6 Surfaces of Terrestrial Planets & $\mathcal{C}$

- The first is **impact cratering**. The Moon shows us evidence of the “early bombardment era”. Why does the Moon have so many more craters than the Earth? (The answer is erosion. See below.) The Moon’s surface also displays **maria**, which are impact-generated lava flows that cooled after filling in lowland basins; they are relatively smooth and therefore reflect less light toward the Earth. [sketch 137] The incoming object that impacts the Earth is called a **meteoroid** when it’s in space, a **meteor** when it’s in the sky, and a **meteorite** when it’s on the surface.

- The second is **tectonism**, which is the ongoing deformation of the **lithosphere** (a.k.a. crust). The crust folds and breaks, forming mountain ranges and trenches. This is common to all five solar system bodies, but only $\mathcal{C}$ has “plate tectonics”.

- The third is **volcanism**, which is a form of “igneous activity” (i.e., earthquakes, volcanos). Gas and molten rock erupt, forming lava sheets and mountains.

- There is one process that destroys surface features: **erosion**. Waves, rapid, rust, freeze-thaw cycles, wind, and glaciers occurred on $\mathcal{V}$, $\mathcal{C}$, & $\mathcal{C}$. Radiation erodes very slowly and affects all five solar system bodies.

- Reading.

- TCPF2: Chapter 5, Section 1, pages 76 - 79.

5.7 Atmospheres of Terrestrial Planets

- prerequisite: Introduction to Terrestrial Planets & $\mathcal{C}$

<table>
<thead>
<tr>
<th></th>
<th>$\mathcal{V}$</th>
<th>$\mathcal{C}$</th>
<th>$\mathcal{C}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>surface pressure (bars)</td>
<td>90</td>
<td>1</td>
<td>0.006</td>
</tr>
<tr>
<td>surface temperature (K)</td>
<td>737</td>
<td>288</td>
<td>210</td>
</tr>
<tr>
<td>carbon dioxide (%)</td>
<td>97</td>
<td>0.04</td>
<td>95</td>
</tr>
<tr>
<td>nitrogen (%)</td>
<td>4</td>
<td>78</td>
<td>3</td>
</tr>
<tr>
<td>oxygen (%)</td>
<td>0</td>
<td>21</td>
<td>0.1</td>
</tr>
<tr>
<td>water (%)</td>
<td>0.002</td>
<td>0.1 to 3</td>
<td>0.02</td>
</tr>
<tr>
<td>argon (%)</td>
<td>0.007</td>
<td>0.9</td>
<td>1.6</td>
</tr>
</tbody>
</table>

- *Today’s* atmosphere came from volcanos and comets.

- Gravity holds an atmosphere down; weak gravity leaves no atmosphere.

The **escape speed** is the speed needed for something to escape the gravity of a body: $v_{esc} = \sqrt{2GM/R}$. So what happens if a planet has a big $M$ as well as a big $R$? Well, we know that $M$ depends on $R$: it’s the density times the volume and the volume depends on $R^3$. Therefore, we see that $v_{esc}$ depends on $R$ (because $\sqrt{R^3/R} = R$). Hence, as $R$ increases, so does $v_{esc}$.

So, what we expect to find is exactly what we find. There is no atmosphere on $\mathcal{V}$ & $\mathcal{C}$, there is a thin atmosphere on $\mathcal{C}$, and there is a thick atmosphere on $\mathcal{V}$ & $\mathcal{C}$.

---

82 WSS 120 3-3 (13′), 4-2 (12′)
83 WSS 120 3-2 (23′)
84 WSS 120 3-1, 3-2 (23′)
85 WSS 120 3-1, 3-2 (23′)
86 This is actually an approximation, valid only if the density is constant.
87 A more accurate estimate of the mass as a function of density is given by

$$M = \int \rho(r, \theta) dV.$$
5.8 Mythology of Terrestrial Planets in Brief

\begin{itemize}
  \item \(\odot\) is the god of war.
  \item \(\odot\) is the goddess of love.
  \item \(\odot\) is the god of trade and the messenger of the gods.
\end{itemize}

5.9 Introduction to Jovian Planets

\begin{itemize}
  \item prerequisite: Cosmic Perspective
  \item prerequisite: Days & Months
  \item prerequisite: Kepler’s Laws of Planetary Motion
  \item prerequisite: Newton’s Universal Law of Gravitation
  \item prerequisite: Magnetic Fields
  \item prerequisite: Doppler Shift
\end{itemize}

\begin{table}[h]
\centering
\begin{tabular}{c|cccc}
\hline
 & \(\odot\) & \(\odot\) & \(\odot\) & \(\odot\) \\
\hline
orbital radius (AU) & 5 & 10 & 20 & 30 \\
orbital period (years) & 12 & 30 & 84 & 165 \\
orbital velocity (km/s) & 13 & 10 & 7 & 5 \\
mass (\(M_\oplus = 1\)) & 318 & 95 & 15 & 17 \\
equatorial diameter (Mm) & 143 & 121 & 51 & 50 \\
equatorial diameter (\(D_\oplus = 1\)) & 11 & 9.5 & 4 & 3.9 \\
oblateness & .07 & .1 & .02 & .02 \\
density (water = 1) & 1.3 & .7 & 1.3 & 1.6 \\
rotation period (hours) & 10 & 11 & 17 & 16 \\
obliquity (degrees) & 3 & 27 & 98 & 29 \\
surface gravity (m/s\(^2\)) & 25 & 11 & 9 & 11 \\
escape speed (km/s) & 60 & 36 & 21 & 24 \\
\hline
\end{tabular}
\end{table}

- Jovian planets are large, massive, cold, and fast rotators relative to terrestrial planets. They are cold because they are so far from the Sun. They are oblate due to fast rotation. There is no solid surface; only atmosphere can be seen.

5.10 Atmospheres of Jovian Planets

\begin{itemize}
  \item prerequisite: Introduction to Jovian Planets
  \item Consider the four jovian planets according to their obvious visible features.
  \item \(\odot\) has the great red spot, which is a giant hurricane larger than \(\odot\) (for at least 350 years), and it has belts and zones, which are dark & light colored bands, respectively.
  \item One of \(\odot\)’s colored bands is like \(\odot\)’s jetstream, and \(\odot\) has storms that produce lightning.
  \item \(\odot\) doesn’t have much.
  \item \(\odot\) had a “great dark spot” (hurricane) almost as big as \(\odot\) that lasted less than five years.
  \item The jovian planets have atmospheres that run deep and contain such chemicals as water (H\(_2\)O), ammonia (NH\(_3\)), methane (CH\(_4\)), hydrogen (H), helium (He), hydrogen sulphide (H\(_2\)S), and ammonium hydrosulphide (NH\(_4\)HS).
  \item Colors on \(\odot\) and \(\odot\) are from impurities.
  \item Rapid rotation causes a strong Coriolis effect. Check out YouTube: “the coriolis force”, and “video of the year 2009 - coriolis effect”.
  \item This leads to fast winds. For \(\odot\) & \(\odot\), this means about 1000 km/hr; for \(\odot\), this means about 2000 km/hr! Note that the obliquity of \(\odot\) (98\(^\circ\)) shows that the Coriolis effect creates wind patterns more than does temperature distribution.
  \item This also leads to storms, which are convective vortices. Consider such an event in the northern hemisphere. \[\text{sketch}\]
\end{itemize}

5.11 Interiors & Magnetic Fields of Jovian Planets

\begin{itemize}
  \item prerequisite: Introduction to Jovian Planets
  \item There is no clear boundary between the atmosphere and interior; there is a gradual change and there is differentiation.
  \item The chemical composition for \(\odot\) & \(\odot\) is 98% H & He, but for \(\odot\) & \(\odot\), it’s only 10% H & He, along with much H\(_2\)O, CH\(_4\), & NH\(_3\).
  \item The interiors are hot enough to drive weather; the heat comes from ongoing gravitational contraction: for example, He condensing and falling out of a H-He liquid mixture. This heat causes collisional ionization, which makes H conduct like a liquid metal in \(\odot\) & \(\odot\). (In \(\odot\) & \(\odot\), deep, salty oceans conduct.)
  \item The jovians (a.k.a. giant planets) have strong \(\vec{B}\)’s relative to \(\odot\), generated by motions of electrically conducting liquids in the interiors. In the cores, \(\vec{B}_\odot \sim 500\vec{B}_\odot\), and \(\vec{B}_\odot \sim 20,000\vec{B}_\odot\). \[\text{WSS 120 3-4 (14')}\]
\end{itemize}
5.13 Moons

- prerequisite: Introduction to Terrestrial Planets & ☉
- prerequisite: Introduction to Jovian Planets

- They are made of rock, ice, or a mix of both. Most have no atmosphere.

[natural satellite wikipedia]

A “regular moon” forms with its planet and orbits in the direction of its planet’s rotation. Some “captured moons” have retrograde orbits.

For many moons, formation involved accretion and differentiation.

- Geologically active moons include Io (☉), Enceladus (?), & Triton (☉). (Note that Io has hundreds of tremendous volcanos with 75-km plumes!)

Some are possibly active, including Europa (☉) & Titan (?). (Note that Europa might have a liquid saltwater ocean under its frozen crust.)

Formerly active moons include Ganymede (☉), Tethys (?), Dione (?), Iapetus (?), Mimas (?), Miranda (☉), Oberon (☉), Titania (☉), & Ariel (☉).

Inactive moons include Callisto (☉) & Umbriel (☉).

- Some moons have the potential to host complex chemistry, including Titan, Europa, and Rhea, and some moons even have salt-water oceans under their icy crusts: Ganymede and Enceladus, for example.

Reading.

- TCPF2: Chapter 6, Section 1, pages 100 - 106.

5.14 Rings

- prerequisite: Introduction to Jovian Planets
- prerequisite: Tides

- Ring systems contain divisions, gaps, and ringlets. They are very thin, as a sheet of paper is to a basketball.

- They are perfectly circular – there is no room for nonconformity.

- The Cassini spacecraft was able to detect rings of dust for the first time when it saw the Sun eclipsed by Saturn.

- Chemical composition of rings varies across the planets. ☉’s might be dark silicates. ☁’s are H₂O ice. The rings of ☉ & ☉ are extremely dark “organic” materials & ☉.

- Rings are affected by moons through orbital resonance. For example, ☉’s Cassini division corresponds to a 2:1 ratio with Mimas. [sketch 145]

- The Roche limit, inside which the tidal force is strong enough to tear apart a moon, plays a roll in ring formation. Maybe the rings are original material – an unformed moon? Maybe they are a captured moon that has been torn apart?

Reading.

- TCPF2: Chapter 6, Section 1, pages 99 - 100.

Homework.

1. (5 points) Consider Saturn’s Cassini division. It’s also possible to have a division corresponding to a 3:2 ratio with Mimas. Would this division be closer to or farther from Saturn than the Cassini division? Justify your answer.

2. (6 points) Imagine two divisions corresponding to 2:1 and 3:2 ratios with Titan, named beta and gamma, respectively. If you were riding on an orbiting ice cube just inside beta, and your friend were riding on an orbiting ice cube just inside gamma, you would both witness Titan display retrograde motion. Which of you would see this more frequently? Justify your answer.

5.15 Dwarf Planets

- prerequisite: Introduction to Terrestrial Planets & ☉
- prerequisite: Introduction to Jovian Planets
- prerequisite: Rings

93WSS 120 2-3 (12')
94See ring figure. Divisions are separations between named rings, and gaps are the spaces within named rings. For the most part, divisions are large and gaps are small.
95Check out Google; image search “backlit saturn”.
96They are “radiation-darkened”.

ootnote{Actually it’s 163° = 180° - 17°.}
ootnote{WSS 120 2-4 (17’), 3-5 (11’), 4-4 (12’)}
ootnote{Hyperion has chaotic rotation.}
ootnote{This ocean contains more water than all of the Earth’s oceans combined.}
Haumea is the goddess of fertility (Hawaii). Makemake is the creator of humanity (Easter Island). Eris is the goddess of discord.

- Reading.
  - TCPF2: Chapter 1, Section 3.

### 5.16 Asteroids & Comets

- prerequisite: Introduction to Terrestrial Planets & C
- prerequisite: Introduction to Jovian Planets

Asteroids are rocky or metallic, or both, but comets are icy\(^\text{98}\). Most asteroids have orbits between \(\delta\) & \(\psi\), in the asteroid belt. Most comets have orbits beyond \(\psi\), in the Kuiper belt or the Oort cloud (see notes on TNO’s for explanations).

Some asteroids and some comets have orbits that pass near \(\oplus\).

- There are three main classes of asteroids: C-type, S-type, & M-type.
  - C-type were never hot enough to melt, so the material is the same as that from which the solar system formed.
  - S-type & M-type were hot enough to melt, and therefore differentiate. The heating was from impacts or radioactive decay, and this led to the evaporation of volatiles (H\(_2\)O, NH\(_3\), CH\(_4\), etc.). When the “S/M asteroid” was smashed in a collision, heavy fragments and light fragments were produced: heavy fragments from the inside being M-type, and lighter fragments from the surface being S-type.

- Comets have several notable parts. As the nucleus – which is like a mountain-sized, dirty snowball – approaches the @, sublimation produces the coma and the tails\(^\text{99}\).
  - The dust tail is made of gas and dust that is pushed by solar photons, and it is curved. The plasma tail (a.k.a. ion tail) is pushed by solar wind, and it is straight. [sketch \(\text{146}\)]

- There is much evidence of recent impacts in our solar system\(^\text{100}\). (Consider the terms meteoroid, meteor, & meteorite.)

  Consider Meteor Crater (APoD image search: “meteor crater”), Tunguska (Google image search: “tunguska”), and Comet Shoemaker-Levy 9 striking \(\psi\) (APoD image search: “shoemaker-levy 9”).

  Consider the extinction of the dinosaurs, the K-T boundary, irridium, and the Yucatán\(^\text{101}\).

- There is evidence of a relationship between comets and the origin of life on \(\oplus\)\(^\text{102}\).

- Reading.
  - TCPF2: Chapter 6, Section 2, pages 106 - 109 and Section 3.

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\(\text{98WSS 120 4-3 (14')}\)
\(\text{99Other notable processes include jets and photodissociation.}\)
\(\text{100WSS 120 4-3 (14')}\)
\(\text{101Note that this coincided with } 10^5 \text{ years of volcanos in India.}\)
\(\text{102UCSD TV presentation.}\)
5.17 TNO’s
- prerequisite: Dwarf Planets
- prerequisite: Asteroids & Comets
- The trans-Neptunian objects\(^{103}\) are the bodies beyond \(\Psi\), and they are found in three zones.

- The first zone is the Kuiper belt, which runs approximately from 30 to 55 AU, in the shape of a flat annulus; the orbits are circular, for the most part. [sketch 147]

\(\Psi\) is the best known KBO, but unlike most KBO’s, it has an atmosphere.

There are tens of thousands of KBO’s; some KBO’s have KBO moons.

Other well-known KBO’s are Haumea, Makemake, Charon, and Quaoar (“kwa-whar”).

- The second zone is the scattered disk, which runs approximately from the KB to more than 100 AU.

The orbits are highly elliptical and highly inclined. [sketch 148]

The scattered disk is the source of periodic comets; that is, SDO’s can become “Centaurs”, which can become periodic comets.

- The third zone is the Oort cloud. (It’s theoretical; it’s probably there, but it’s not yet observed.) It extends out to approximately one light year.

The Oort cloud is the likely source of long-period comets.

It formed early in the solar system’s history as a result of objects scattered outward by giant planets.

Oort cloud objects are easily disturbed by other stars. (If the object’s orbit is disrupted, it may fall toward the \(\odot\)).

- Reading.
  - TCPF2: Chapter 6, Section 2, pages 107 - 108.

5.18 Meteors
- prerequisite: Collisional vs. Radiative Processes

Consider the actual size of a typical shooting star. [sketch 149] 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)!\(^{104}\)

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

Consider that a comet (sort of a mountain-sized dirty snow-ball) will sublince as it approaches the Sun. [sketch 150] (Notice the direction of the tail.) So we see that comets litter the solar system with debris. And we see why showers occur annually.

6 Stars

6.1 Star Formation in Brief
- prerequisite: Cosmic Perspective
- prerequisite: Newton’s Universal Law of Gravitation
- prerequisite: Doppler Shift

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

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

- Consider a star formation region. [sketch 151] Eventually, the cloud collapses due to gravity. [sketch 152] In addition to the star, other solar system objects (planets, moons, asteroids, and comets) form as part of this process\(^{105}\)

- 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)!\(^{106}\) (It’s a bit like rolling two balls up a hill with a well on top?) [sketch 153] 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.

6.2 Star Formation
- prerequisite: Cosmic Perspective
- prerequisite: Newton’s Universal Law of Gravitation
- prerequisite: Magnetic Fields
- prerequisite: Doppler Shift

Macroscopically speaking, a galaxy is composed of three things: stars, dust, and gas. The dust and gas make up the interstellar medium, or ISM. The ISM contains interstellar clouds, some of which are star formation regions.

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

\(^{103}\)WSS 120 2-5 (14')

\(^{104}\)Consider the similarities to lightning.

\(^{105}\)WSS 180 1-2 (11')

\(^{106}\)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?
• First we consider four basic concepts related to star formation. For our Sun, the process lasted about 35 million years.
  - A star formation region is likely to be somewhat ionized by cosmic rays, which are usually very high-speed protons coming from supernovae [109] [sketch 154].
  - The Milky Way has a bar that runs, for the most part, along the spiral arms of our galaxy [110][111] [sketch 155]. As a result of the ionization along with the presence of the galactic $B$, the star formation region is a plasma, which is a charged, magnetic gas. (Remember the way in which charged particles interact with $B$’s?)
  - Eventually, the star formation region collapses due to gravity. [sketch 156] In addition to the star, other solar system objects (planets, moons, asteroids, and comets) form as part of this process.
  - During the contraction, the region obeys the law of conservation of angular momentum, which can be thought of as the “spinning ice-skater effect”. [sketch 157] If the mass is constant, then the rotation rate varies inversely with the size or radius $[112]$.

We consider the actual process of star formation in three stages, the first of which is a combination of the previously considered four basic concepts.

  - The star formation region undergoes a modified gravitational collapse.
    The collapse must begin along the field lines. Why? [sketch 158] In the beginning, the particles are relatively far apart, allowing the $B$ to dominate the collapse. One might ask why the neutral particles also follow the field lines; the answer is collisional coupling between the charged and the neutral particles. (Imagine trying to walk diagonally through a mass of people all headed in the same direction; surely you would be forced, as a result of collisions, into their stream. [sketch 159])
    When the particles are, on average, closer together, the collapse is then dominated by the gravitational field (rather than the $B$). Why? This produces a “pinched” $B$. [sketch 160]
    Since the collapse isn’t 100% efficient, there is still some leftover plasma outside the collapsed region. [sketch 161] The $B$ permeating the leftover plasma tends to drag it. Why? This effect is much like a snowplow or a sail, and it’s called magnetic braking. As a result, the rotation of the collapsed region is slowed. If not for magnetic braking, conservation of angular momentum would have increased the rotation rate so much that the region would be more likely to fly apart than to collapse further to form a star.
    - In the core of the collapsed region, the density and temperature have become much greater. (Remember the meaning of temperature?)
    - When protons are fast enough to overcome their mutual electric repulsion, they can stick together (fuse) $[113]$ (It’s a bit like rolling two balls up a hill with a well on top?) [sketch 162] 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.

6.3 Nuclear Fusion

- prerequisite: Cosmic Perspective
- prerequisite: Doppler Shift

- 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: charge conservation and nucleon conservation (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 163] Consider conservation.

The second stage begins with a deuterium nucleus and a proton colliding and ends with a $^4$He nucleus and a gamma ray. [sketch 164] Consider conservation.

107WSS 180 1-2 (11) 108There is a quite a range in the amount of time it takes, depending on the mass of the star. If the star will be about $10^6 M_\odot$, then it can take as little as $10^5$ years. If the star will be about $5 M_\odot$, then it will take longer than it did for the Sun.
109A supernova is an extremely energetic, explosive event at the end of the life of a very massive star.
110Our Milky Way is actually a barred spiral galaxy.
111The origin of this galactic $B$ remains a mystery.
112An alternate way of thinking of this is in terms of Kepler’s second law of planetary motion: the law of equal areas. Extended arms sweep slowly, and retracted arms sweep quickly.
113They 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?
The third stage begins with two $^3\text{He}$ nuclei colliding and ends with a $^4\text{He}$ nucleus and two protons. [sketch 165] Consider conservation.

- We can imagine all three stages together in one reaction which obeys the rules. [sketch 166] Consider conservation.

- Consider some details.

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

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.

$$4^4\text{He} \rightarrow 4^4\text{He} + 6\gamma$$

The essence of this is simple.

fuel $\rightarrow$ exhaust + energy

- It turns out that the mass of four protons ($6.69 \times 10^{-27}$ kg) is more than the mass of the $^4\text{He}$ nucleus ($6.64 \times 10^{-27}$ kg). Where did the missing mass ($0.05 \times 10^{-27}$ kg) go? (It’s not related to the electrons that we ignored, they’re combined mass is only about $0.02 \times 10^{-27}$ kg.) It actually turned into energy! The amount of energy produced is about $4 \times 10^{12}$ Joules, which is about one trillionth of a dietary calorie (Cal).

- The Sun’s luminosity (total power output) is about $4 \times 10^{26}$ Watts (a Watt is one Joule per second). So how many reactions, at $4 \times 10^{-12}$ 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 $^{113}$

- Reading,

  - TCPF2: Chapter 1, Section 1, pages 129 - 130.

- Homework.

1. (5 points) Describe the conservation of charge in the (a) first step of the proton-proton chain, (b) second step of the proton-proton chain, and (c) third step of the proton-proton chain.

2. (5 points) Describe the conservation of nucleons in the (a) first step of the proton-proton chain, (b) second step of the proton-proton chain, and (c) third step of the proton-proton chain.

3. (4 points) Consider the reaction $^6\text{Li} + ^2\text{H} \rightarrow ^4\text{He} +$ _____ . How many charges must exit this reaction? How many nucleons must exit the reaction? Which element must fill in the blank? Which isotope must fill in the blank? Justify your answers.

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$^{114}$ We need only divide the power by the energy per reaction to find the answer.

$^{115}$ WU 180 2-3 (11')

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### 6.4 Limb Darkening

- prerequisite: Doppler Shift

Here we distinguish between the core & surface of the Sun and the center & limb of the Sun’s disk. [sketch 167] 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. [sketch 168] We can see deeper into the Sun in region 1, relative to region 2.

- 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” $^{116}$

- 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?

### 6.5 Sunspots in Brief

- prerequisite: Magnetic Fields

- prerequisite: Doppler Shift

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 $^{117}$

As a result, the equatorial $\vec{B}$ races ahead and even wraps around the Sun. [sketch 171] As 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 $^{118}$ [sketch 172]

- 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. [sketch 173] 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.

$^{116}$ Consider granulation. What is convection? [sketch 169] Our Sun has a convective mantle. [sketch 170] While one surface region is hotter and brighter, the adjacent region is cooler and fainter.

$^{117}$ The Sun also has radial differential rotation.

$^{118}$ APoD; image search “sunspots”; WSS 100 1-3 (16’
6.6 Sunspots

- prerequisite: Magnetic Fields
- prerequisite: Doppler Shift

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

- Consider the initial configuration of the solar $\vec{B}$; it runs under the surface, and then out and around. [sketch 174]

- 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.[120]

- Consider the variable configuration of the solar $\vec{B}$. Let’s start by looking only at the internal part of the $\vec{B}$, and only at one single $\vec{B}$ line. [sketch 175] It runs from S to N. Let’s combine the ideas of the previous three bullets. [sketch 176] (What would we expect for a strange horse race? [sketch 177]) The equatorial $\vec{B}$ races ahead and even wraps around the Sun. [sketch 178] As 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.[121]

- 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. [sketch 180]

- The solar wind pushes on the magnetic loops (why?), and forces them to grow outward; now we must recall the external section of the field line. [sketch 181] Notice the regions in which two field lines are oppositely directed. This results in a disconnection event. These regions effectively have zero field. [sketch 182]

- In general, $\vec{B}$ lines must always be continuous, so there are reconnection events. [sketch 183] This leaves zones where the solar wind can easily escape, thereby allowing the external field lines to fall back toward the Sun’s surface. But notice the polarity of the falling lines is N to S.

- Consider the N hemisphere field; it’s mostly E to W. The S hemisphere field is mostly W to E. Yet the overall field is still S to N. [sketch 184] However, little by little and eventually, the falling N to S polarity wins out over the original S to N polarity. But the E to W in the N and the W to E in the S are preserved. [sketch 185] The result is a field reversal.

- Recall the differential rotation. (What would we expect for a modified strange horse race? [sketch 186]) So we see the Sun can progress from active back to quiet – from maximum back to minimum. [sketch 187] But notice the overall polarity is now N to S!

- This cycle takes, on average, 11 years; it is the sunspot cycle. Of course, over the next 11 years, the whole thing happens again. The result is another quiet Sun with S to N polarity. [sketch 188] So we see the overall magnetic cycle is 22 years.

- Consider the Maunder minimum (1645 to 1715). [sketch 189] Consider also the “butterfly diagram”. [sketch 190]

- 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.[122]

- Reading.

  – TCPF2: Chapter 8, Section 1, pages 131 - 134.

- Homework.

  1. (5 points) If the Sun’s equatorial and polar rotation periods were exchanged, so that the equator rotated roughly every 35 days and the polar regions rotated roughly every 25 days, would the Sun still have spots? Would there still be a sunspot cycle? If so, would it be shorter than, longer than, or equal to eleven years. Would there still be a magnetic cycle? If so, would it be shorter than, longer than, or equal to twenty-two years. Justify your answers.

  2. (8 points) If the Sun’s equatorial and polar rotation speeds were the same and equal to 2 kilometers per second, would the Sun still have spots? Would there still be a sunspot cycle? If so, would it be shorter than, longer than, or equal to eleven years. Would there still be a magnetic cycle? If so, would it be shorter than, longer than, or equal to twenty-two years. Justify your answers.

  3. (5 points) If there were no solar wind, would the Sun still have spots? Would there still be a sunspot cycle? If so, would it be shorter than, longer than, or equal to eleven years. Would there still be a magnetic cycle? If so, would it be shorter than, longer than, or equal to twenty-two years. Justify your answers.

6.7 Stellar Evolution & the H-R Diagram

- prerequisite: Star Formation in Brief
- prerequisite: Nuclear Fusion


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] 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 \( \text{H} \rightarrow \text{He} \) 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] 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. On the HR diagram, the more massive stars are at the top; the less massive at the bottom. [sketch] 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] 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.

6.8 Life of Our Sun

prerequisite: Stellar Evolution & the H-R Diagram

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

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 \( 10^3 L_\odot \), 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 \( T \) 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.

And the surface gets red. [sketch]

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

\[ L = 4\pi R^2 \sigma T^4 \]

\[ L = 4\pi R^2 \sigma T^4 \]

\[ \text{The pressure and density in the core don’t increase as the temperature rises because the electrons are “degenerate”. Of course, the nuclei aren’t!} \]
with a collision between two $^4$He nuclei\textsuperscript{125} and results in a $^8$Be nucleus. [sketch 197] Consider conservation. Since the $^8$Be nucleus is so unstable (it will decay in $10^{-16}$ seconds!), it should break apart into the $^4$He nuclei. But when the temperature is so hot — and the particles are so fast, a third $^4$He collides with the $^8$Be. This is the second stage, and the result is a $^{12}$C nucleus and a $\gamma$-ray. [sketch 198] Consider conservation. If another $^4$He 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 199] Examples of such stars today are Albebaran in Taurus and Arcturus in Boötes. [sketches 200 & 201] 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 202]

- 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 203] (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\textsuperscript{227} 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 204] 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 $M_{WD} \leq 1.44 M_\odot$ if the WD is made of C & O.

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

\textsuperscript{125}A $^4$He nucleus is a.k.a. an $\alpha$-particle.

\textsuperscript{126}WU 180 1-4 (12')

- **Homework.**
  1. (7 points) Consider part of the life of a proton. Begin with it floating in the core of our Sun when the Sun first formed and follow it to the white dwarf stage. Assume it is not involved in fusion. Make a graph of the proton’s speed vs. time.
  2. (9 points) Consider part of the life of a proton. Begin with it floating in the photosphere of our Sun when the Sun first formed and follow it to the planetary nebula stage. Assume it does not leave as wind, but is ejected with the planetary nebula. Make a graph of the proton’s speed vs. time.
  3. (10 points) The third stage in the section *Life of Our Sun* follows a specific chain of logic, as given in the notes. The sixth stage follows a similarly specific chain of logic; construct this chain of logic.
  4. (8 points) Consider the seventh stage in the section *Life of Our Sun*. Also consider the Ring Nebula, M57, which is an easily-seen planetary nebula in the constellation of Lyra. If the white dwarf had a surface temperature of 3,000 K instead of 25,000 K (so that its black-body curve peaked in the IR instead of the UV), would we still be able to detect M57? Justify your answer.

### 6.9 Supergiants & Supernovae

- prerequisite: Life of Our Sun

- 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 $.01 R_\odot$, but the size of the star is tremendous: about $10^4 R_\odot$! 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 205 & 206]

- 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 about $10^6$ 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 (*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^{11} K, a set of reactions beginning with two \(^{16}\)O nuclei will result in the formation of \(^{28}\)Si and \(^{31}\)S.

The next reaction begins in the core at a temperature of nearly 4 \times 10^{10} 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 207] 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\(^{130}\).

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 208] 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\(^{131}\). 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\(^{132}\).

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!

6.10 Neutron Stars & Pulsars

- prerequisite: Magnetic Fields
- prerequisite: Supergiants & Supernovae

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 a 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 \(10^{12} \vec{B}\). 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 209] 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\(^{133}\).

- 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.

6.11 Binary Stars

- prerequisite: Star Formation in Brief

- 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\(^{134}\). 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 with larger, cooler star. [sketch 210] What would be the shape of the light curve? [sketch 211]

- 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, .

\(^{130}\)56 nucleons is also a dead end for fission reactions.

\(^{131}\)The halt of the collapse is probably a combination of neutron degeneracy and a repulsive neutron-neutron interaction mediated by the strong nuclear force.

\(^{132}\)WU 180 2-4 (15’)

\(^{133}\)WU 100 3-3 (12’)

\(^{134}\)Consider \(\alpha\)-Centauri, or Castor in Gemini.
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. 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.

### 6.12 Novae

- **prerequisite:** Life of Our Sun

- **prerequisite:** Binary Stars

Imagine living 2000 years ago in Rome, where you watched the sky every night. You learned the constellations. One evening, when you are 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. 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.

- **Reading.**
  
  - TCPF2: Chapter 10, Section 1, page 168.

- **Homework.**

  1. (5 points) Is there any way possible for our Sun to become a nova? Justify your answer.

### 6.13 Cosmic Recycling

- **prerequisite:** Supergiants & Supernovae

- 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.

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

- **Homework.**

  1. (4 points) Imagine if stars had no wind, and they never “exploded” as planetary nebulae, novae, supernovae, or in any other way. Would there be more, less, or the same amount of life on Earth? Justify your answer.

### 7 Galaxies

#### 7.1 Overview of Galaxies

- **prerequisite:** Cosmic Perspective

- Galaxies come in four basic types: elliptical, barred spiral, unbarred spiral, and irregular. All types come in a wide range of sizes. Our Milky Way is a barred spiral galaxy.

- Stars in elliptical galaxies have complex, irregular orbits. The density of stars in elliptical galaxies is so high that type I supernovae keep the gas hot, and there is little or no star formation.

- Stars in spiral galaxies move on nearly circular orbits in the “disk”, but have irregular orbits in the “bulge”. The gas is cool, and stars form along the spiral arms; the formation is triggered by spiral density waves.

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

#### 7.2 AGN

- **prerequisite:** Cosmic Perspective

- **prerequisite:** Newton’s Universal Law of Gravitation

- **prerequisite:** Doppler Shift
• A quasar\(^{137}\) 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. [sketch 219] 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. [sketch 220] If our line of sight is such that we are looking along one of the jets, then we see a blazar\(^{138}\) [sketch 221]

• Reading.
  – TCPF2: Chapter 11, Section 3.

7.3 Dark Matter

• prerequisite: Neutron Stars & Pulsars

• 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. [sketch 222] (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. [sketch 223] 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). [sketch 224] All 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\(^{139}\) 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\(^{140}\) 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 (\(\approx 10^6\) 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 “intracluster” 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.

8 Black Holes & Cosmology

8.1 Early Universe

• prerequisite: Newton’s Universal Law of Gravitation

• prerequisite: Nuclear Fusion

• prerequisite: Matter & Antimatter

• Planck Time: before \(10^{-43}\) sec\(^{141,142}\) It is thought that only one force existed in the universe: the TOE force (We are not

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\(^{137}\)The word is an abbreviation of quasi-stellar radio source.

\(^{138}\)The word is meant to combine two classes of phenomena: quasars and BL Lac objects.

\(^{139}\)Here, 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.

\(^{140}\)Microlensing is a “small” version of gravitational lensing.

\(^{141}\)Consider that the mass in the universe is a form of energy (as in \(E = mc^2\)), but the gravity between these masses is a form of negative energy (as in gravitational potential energy). Perhaps the total energy in the universe is actually zero.

\(^{142}\)WSS 170 6-4 (12')
even close to finding the “theory of everything”, since we
don’t yet know the GUT. The TOE might not even exist.).

- **GUT Era begins**: \( t = 10^{-13} \text{ sec}, T = 10^{32} \text{ K} \). It is thought that two forces existed in the universe: gravity and the GUT force. (We are not even close to finding the “grand unified theory”, since we don’t yet understand quantum chromodynamics well enough to say why a proton has spin one-half. The GUT might not even exist.)

- **Electroweak Era begins**: \( t = 10^{-38} \text{ sec}, T = 10^{29} \text{ K} \). There were three forces in existence during this era: gravity, the strong nuclear force, and the electroweak force. The universe contains leptons from now on.

The strong nuclear force holds protons and neutrons together in atomic nuclei.

(The GUT era lasted how many times longer than the Planck era?)

- **Particle Era begins**: \( t = 10^{-10} \text{ sec}, T = 10^{15} \text{ K} \). There were four forces in existence during this era (and so it is today): gravity, the strong nuclear force, the weak nuclear force, and the electromagnetic force. The universe contains leptons from now on.

The weak nuclear force is responsible for radioactive decay.

The electromagnetic force holds electrons in orbit of nuclei to make atoms, and it includes all electric and magnetic forces.

- **Late Particle Era**: \( t = 10^{-3} \text{ sec}, T = 10^{12} \text{ K} \). Collisions cool and slow enough that protons and neutrons can exist without breaking into quarks.

- **Very Late Particle Era**: early in 1st sec.

There is much pair production & pair annihilation. [sketches 225 & 226]

- **End of Particle Era**: after 1st sec. The γ’s collide less and pair production halts. Pair annihilation proceeds (why?) and antimatter disappears. The universe contains matter from now on.

Symmetry breaking:

\[
\frac{\text{particles}}{\text{antiparticles}} = \frac{1,000,000,001}{1,000,000,000}
\]

Protons, electrons, and neutrons are left over.

- **Era of Nucleosynthesis**: 1st 3 minutes, \( T = 10^9 \text{ K} \). The γ’s mostly kept nuclei from forming, but some He, Li, Be were formed. All other than first 4 were formed later

- **Era of Nuclei**: 1st 500,000 yrs. No neutral atoms formed due to continual ionization.

- **Era of Atoms**: after 500,000 yrs, \( T = 3000 \text{ K} \). Photons are spread out due to expansion, and atoms form as recombination occurs everywhere; the universe becomes transparent – photons race across universe and we see them as CMBR. [sketch 227]

- **Era of Galaxies**: Nowadays photons outnumber atoms by \( 10^9 \) to 1.

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**8.2 Curved Spacetime**

- What is *spacetime*? It’s the four-dimensional “continuum” in which we exist. These four dimensions are time (we move into the future), length (we can move left or right), width (we can move forward or backward), and height (we can move up or down). We are 4-D creatures, and we are always moving through all four dimensions.

<table>
<thead>
<tr>
<th>space</th>
<th>flat</th>
<th>curved</th>
<th>embedding space</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-D</td>
<td>[sketch 228]</td>
<td>[sketch 229]</td>
<td>2-D</td>
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<tr>
<td>2-D</td>
<td>[sketch 230]</td>
<td>[sketch 231]</td>
<td>3-D</td>
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<td>3-D</td>
<td>[sketch 232]</td>
<td>??</td>
<td>6-D</td>
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<td>4-D</td>
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<td>10-D</td>
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- Before we consider curved spacetime, we should understand something about *curved space*. In some cases, such an understanding can be made clear through the use of an “embedding space”.

- So we see that as humans we are incapable of visualizing the most basic aspect of the reality in which we exist. Consider Flatland: A Romance of Many Dimensions by E. A. Abbott (1884), a crazy man at the bottom of the Grand Canyon, new African cichlids in an aquarium, and the fact that orbits are straight lines.

- What is the sum of all three angles in a triangle? The answer depends the curvature of the space. If there is no curvature, as in Euclidean geometry, the answer is \( a + b + c = \pi \). [sketch 233] In spherical geometry the answer is different. [sketches 234 & 235] We find \( a + b + c > \pi \). How much greater than \( \pi \)? [sketches 236, 237, & 238] Yet again the answer is different in hyperbolic geometry: \( a + b + c < \pi \). [sketches 239 &

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143 It may be comforting to think that time is somehow different from length, width, or height, but it’s not. In light of experiments in physics, we find that – despite the fact that we can’t choose between moving into the past or the future – time is fundamentally the same as the other three dimensions. After all, can we really have time without length? Can we really have length without time?

144 When embedding an \( N \)-dimensional curved space in a flat space, the number of dimensions of the flat “embedding space” is equal to the number of independent elements in the \( N \)-dimensional metric. [The metric is a *tensor* of rank \( 2 \) that determines how we deal with distances and angles in a space. A tensor is a mathematical object that allows us to write the laws of the physics in ways that do not depend on the (possibly non-inertial) reference frame of the observer; it’s something that retains its character under coordinate transformation.]

145 If the 3-D space has constant curvature, then the embedding space is only 4-D.

146 This might remind you of the “Allegory of the Cave” in Book VII of Plato’s *The Republic*.
8.3 General Relativity

- The amount greater than or less than \( \pi \) depends on the curvature. \(^{149}\)

- What is the ratio of the circumference of a circle to its diameter? The answer depends on the curvature of the space. If the space is flat, as in Euclidean geometry, the answer is \( C/D = \pi \) (because \( C = \pi D \)). \(^{241}\) In spherical geometry, the answer is different. \(^{242}\) We find that \( C/D < \pi \). How much less than \( \pi \)? \(^{243}\) Yet again the answer is different in hyperbolic geometry: \( C/D > \pi \). \(^{244}\)

- Just as space can be curved, so we live in curved spacetime.

- Homework.

1. (5 points) Consider a spherical surface upon which a circle is drawn. As discussed, \( C/D < \pi \). How small can the ratio \( C/D \) get on a spherical surface? Justify your answer.

8.4 Black Holes in Brief

- prerequisite: Cosmic Perspective

- prerequisite: Newton’s Universal Law of Gravitation

- prerequisite: Doppler Shift

Is there any difference between a braking train and a temporarily forward gravitational force?

- General relativity provides at least a few intriguing implications. The first is that as gravity increases, time slows. This is a form of time dilation. (That is, \( \text{Special Relativity}. \)) Consider a student standing on the ground while the professor rides on a carousel. Will they agree on the passage of time if the professor is at the very center of the carousel? \(^{246}\) What happens as the professor moves away from the center? \(^{247}\)

The second is that curvature is gravitation; gravitation is curvature. \(^{150}\) This is a form of length contraction. (Again, recall the section \( \text{Special Relativity}. \)) Consider a student standing on the ground while the professor rides on a carousel. Will they agree on the diameter of the carousel? \(^{248}\) Will they agree on the circumference of the carousel? \(^{249}\) If they don’t agree, what does this mean?

The third is that gravity itself generates gravity. So mass is not the only thing that generates gravity. And of course, there is gravity generated by the gravity generated by the gravity. And so on. This is one reason why it’s so extremely difficult to actually calculate the gravitational field of an object.

- When Einstein published the general theory, he also explained a well-known discrepancy between predictions based on Newton’s law of gravity and observations of the precession of Mercury’s perihelion. \(^{250}\) The discrepancy was \( 43''/\text{century} \). Einstein was able to show that the excess precession due to general relativistic effects alone is \( 43''/\text{century} \): an amazing accomplishment!

He also suggested some experiments that could be conducted in order to further verify his theory. One such experiment was to measure the locations of stars during a total solar eclipse. \(^{251}\) The measured deviations were in agreement with the theory. The universe really is curved!

Another experiment to test the theory involves two synchronized atomic clocks at different elevations. \(^{252}\) Which clock should run faster? The experimental results agree with the theory. Gravity really does slow time!

- Reading.

- TCPF2: Chapter 10, Section 2, page 173.

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\(^{148}\)This pseudosphere is a surface of revolution based on a \( \text{tractrix} \).

\(^{149}\)The actual equation is \( a + b + c = \pi + K \cdot A \). Here \( K \) the curvature of a \( \text{uniform surface} \) (with \( K = \pm 1/R^2 \), where \( R \) is the \( \text{radius of curvature} \)), and \( A \) is the \( \text{area of the surface} \).

\(^{150}\)WSS 170 7-3 (skip until 32°35’=1°35), 7-4 (skip 53°50’=7’ to 56°55’=10°05”) (24’)

\(^{151}\)Also of note are Newton’s rotating bucket of water and \( \text{Mach’s principle} \).

\(^{152}\)For reasons we need not go into, the free-falling systems must be non-rotating and local.

\(^{153}\)Lex Luthor: Drop of Doom held the record as the tallest drop tower in 2012.

\(^{154}\)For reasons we need not go into, the gravitational systems must be considered locally.

\(^{155}\)An acceleration of one \( g \) is the same as the acceleration due to gravity at the Earth’s surface.

\(^{156}\)WSS 170 6-2, 6-3 (23’)

\(^{157}\)In order to avoid issues related to the \( \text{Ehrenfest paradox} \), we may consider the professor running very quickly around the edge of a stationary carousel.
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, \( F_g \) & \( v_{\text{esc}} \) get less. At greater distances from the singularity, \( F_g \) & \( v_{\text{esc}} \) get less. [sketch 253] 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 \([sketch 254]\)

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 Schwarzschild radius, \( R_{\text{Sch}} \).

Consider infinite curvature in one dimension and in two dimensions. [sketches 255 & 256] 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 257] 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. 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 Schwarzschild radii.

8.5 Black Holes

- prerequisite: Cosmic Perspective
- prerequisite: Doppler Shift
- prerequisite: General Relativity

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At any distance away from the singularity, \( F_g \) & \( v_{\text{esc}} \) get less. At greater distances from the singularity, \( F_g \) & \( v_{\text{esc}} \) get less. [sketch 258] 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 \([sketch 259]\)

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). Recall that GR tells us that spacetime is curved, and this curvature slows the passage of time; also recall that GR tells us that gravitation is curvature and curvature is gravitation! This type of black hole is known as a Schwarzschild black hole. In this case, the event horizon is known as the Schwarzschild radius, \( R_{\text{Sch}} \). (There is also a photon sphere at 1.5 \( R_{\text{Sch}} \). If a photon is emitted at this location, in a particular direction, it can orbit the black hole.)

Consider infinite curvature in one dimension and in two dimensions. [sketches 260 & 261] A singularity is infinitely curved, four-dimensional spacetime.

The formation of a black hole is difficult to understand because time slows as curvature increases. But if an event horizon forms, then it probably starts as a point and grows

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160 For a 10\( M_\odot \) black hole, \( R \approx 3,000 \) km.
161 There are four basic types of black holes: Schwartzschild, Reissner-Nordstrom, Kerr, and Kerr-Newman. The second includes charge, and the third includes rotation; the fourth includes both.
Consider a student hovering far above an event horizon, watching the professor falling toward $R_{S_{bh}}$. What does the student see? What does the professor see?

- In the student’s reference frame, she would see no time passing at the event horizon. The professor would appear to slow down (time dilation) and become very faint (extreme gravitational redshift). Eventually, he would appear to completely freeze and fade to black. That is, the student can’t detect the professor crossing until after an infinite amount of time has passed. So we must wonder, how can anything ever fall inward across the event horizon, if everything appears to stop falling just as it arrives?

- In the professor’s reference frame, he sees the light from the student showing she is blueshifted and aging too fast. But in his frame, it only takes a normal (finite) amount of time to cross the event horizon. So he doesn’t see billions of years pass in the student’s frame before he crosses.

- Analysis shows [263] that even in the student’s frame, the professor isn’t lingering forever just above the event horizon. However, that is exactly what the photons are doing that were emitted by him, and that’s why he appears in her frame to hover forever. Yet, if light takes forever, and nothing travels faster than light (including gravity), then it seems that in the student’s frame there is no detectable effect whatsoever that the professor crossed. So, again, the same question arises in the student’s frame: how can anything ever fall inward across the event horizon?

  * Perhaps nothing does; perhaps so much material accumulates just outside the event horizon that this accumulated mass generates its own event horizon farther out. In this case, nothing falls into a black hole; the event horizon engulfs matter as it moves outward.

- The extreme tidal forces and “spaghettification” will be apparent in both reference frames. [sketch 263]

- What happens to the professor after he crosses the event horizon? Inside the event horizon, curvature of spacetime is such that all directions lead inward; this is why nothing can escape – the spacetime curves back in on itself [164]. Here, time and space have been interchanged. The singularity is unavoidable because it’s not a location, it’s a time: the professor’s future. You can walk around a location to avoid it, but you can’t walk around noon – it’s going to happen no matter what.

  * In the classroom on campus, you watch the second hand of the clock tick; you can sit still, but you’re moving through time from past to future. If you wish, you can choose to move around the room – change your location. Pretend the classroom were transported to inside a black hole. Now location behaves the way time behaves back on campus, and time behaves the way location behaves back on campus. Perhaps you can choose to not move through time, or perhaps you can choose to move toward the past or toward the future. But it doesn’t matter because you must move inward toward the singularity – it’s going to happen no matter what. So, it’s not the gravitational pull of the mass that makes the singularity unavoidable; rather, it’s the character of time and space. (This is especially evident when considering a charged black hole [165]).

- So what happens to a collapsed neutron star after the event horizon forms? It becomes a singularity; it can’t avoid the future [166].

  • 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 264] 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. 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.

  • Finally, we consider rotating black holes. As far as we know, all stars rotate. So conservation of angular momentum demands that all black holes rotate. Unlike the Schwartzschild black hole, the Kerr black hole has a ring singularity, and it has two event horizons – neither of which coincides with the two surfaces of infinite red shift (except at the poles) [sketch 265]. Nothing can fall straight in because the rotation drags the space around.

- Reading.

  • TCPF2: Chapter 10, Sections 2 - 3.

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[165] The theory of charged black holes is equally fascinating. If the charge is “more than” the mass, there is a singularity, but there is no event horizon! (And there are no surfaces of infinite redshift.) If the charge is “less than” the mass, there are two event horizons. Approaching the outer event horizon is much like approaching $R_{S_{bh}}$; it is the point of no return for light and everything else. Crossing the outer event horizon is much like crossing $R_{S_{bh}}$; the properties of time and space are interchanged. Inside the inner event horizon, properties of time and space are “normal” again; so even though nothing can escape the inner event horizon, it is possible to avoid the singularity. (Neutral matter can’t even reach the singularity; it’s stopped short at a minimum distance away!) If the charge is “equal to” the mass, then the inner and outer event horizons coincide and there’s no region in between.

[166] Of course, no one has worked out a theory that combines GR with quantum mechanics, so we can’t say for sure that a quark degenerate object doesn’t form.

[167] Regions I, II, and III are just like in the charged case, except neutral matter can fall all the way to the singularity.
• 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 Schwarzschild radii.

8.6 Gravitational Redshift

• prerequisite: Cosmic Perspective

• prerequisite: Newton’s Universal Law of Gravitation

• prerequisite: Doppler Shift

• 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 [168] [sketch 266].

• 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. [sketch 267]

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 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.

8.7 Hubble’s Law & Hubble Distance

• prerequisite: Cosmic Perspective

• prerequisite: Newton’s Universal Law of Gravitation

• Cosmology is the science of the universe as a whole. The universe is expanding; spacetime itself is expanding.

• Hubble’s law is \( v = H_0 d \), or equivalently, recessional velocity equals the Hubble constant times distance [169]. 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 268]

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 [170].

• Hubble’s law describes an average. So the fact that Andromeda doesn’t fit the trend (it’s approaching rather than receding) isn’t a problem. Recessional velocity dominates over local velocity for more distant galaxies; hence, Hubble’s law becomes more accurate for more distant galaxies.

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

• Homework.

1. (4 points) Imagine \( H_0 = 100 \) km/s/Mpc. What would be the recessional velocity of a galaxy \( 10^9 \) parsecs away? Justify your answer.

8.8 Cosmological Redshift

• prerequisite: Doppler Shift

• prerequisite: Hubble’s Law & Hubble Distance

• 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 to reach its destination, and during this time the universe will expand significantly [171] [sketch 269].

Consider a wavy line on a deflated balloon. What happens when the balloon is inflated? [sketch 270]

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.

168Energy of motion is called kinetic energy: \( K = \frac{mv^2}{2} \).
169Strictly speaking, Hubble’s law is \( cz = H_0 d \), where \( z \) is the redshift.

170Or perhaps everywhere in the universe is the center. After all, the big bang likely happened at one point, but that point was every point in the universe. So, perhaps the big bang happened at every point in the universe. Have you ever felt like you are the center of the universe? Maybe you are! But then so is everyone else.
171We are not talking about the photon’s reference frame.
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\(^{172}\) takes into account Einstein’s general theory of relativity, whereas the formula for relativistic Doppler shift\(^{173}\) only takes into account Einstein’s special theory of relativity. The two formulas only produce similar answers for nearby galaxies.\(^{174}\)

8.9 Big Bang

- prerequisite: Cosmological Redshift

- 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 (and bluer). 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.\(^{175}\)

- 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 every time 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...

8.10 Cosmic Microwave Background

- prerequisite: Big Bang

- 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.

\(^172\)If \(z\) is the redshift, then \(1+z = R(t_{obs})/R(t_{em})\). Here, \(R\) is proportional to the scale factor, which is related to the ratio of sizes of the universe at two different times.

\(^173\)If \(z\) is the redshift, then \(1+z = \sqrt{(1+v/c)/(1-v/c)}\).

\(^174\)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: \(z \approx 1.5\).

\(^175\)WSS 170 7-1, 7-2 (27') (skip at 26'45"=11'15")

\(^176\)This name was coined by an opponent of the theory, but now we seem to be stuck with it.

\(^177\)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.

\(^178\)WU 170 4-4, ALL 4-5 (28')

\(^179\)Maybe the universe is infinite in size even though it’s not infinitely old. If this is the case, then it was infinite in size even when it began. The big bang happened at many (infinite) points. Each of those points has expanded for the past 13.8 billion years. But the universe began as one and is still only one.
must there be an actual edge? Not necessarily. Consider a spherical shell as an example of a curved 2-D space. [sketch 272] Consider how far must an inhabitant travel in such a universe before reaching the edge. It must be possible to have a finite universe with no actual edge!

Our universe is a curved, 4-D spacetime. We can’t visualize it, or make a sketch of it. But we can still study it, analyze it, theorize about it, and write down many appropriate equations to describe it.

8.12 Cosmic Horizon & Dark Energy

• prerequisite: General Relativity

• prerequisite: Hubble Parameter & Observable Edge

If the universe were decelerating, then more and more galaxies would come into view—to be seen as they exist today (as the Hubble distance moves outward). However, there is a cosmic horizon (for events happening today), beyond which we will never see, because expansion of the universe is accelerating.

In an accelerating universe, the Hubble distance will eventually stop increasing. The current distance to our cosmic (event) horizon is 16 billion light years—well within the observable edge! But light emitted today from galaxies beyond the cosmic horizon will never reach us. [sketch 273]

We will see events in those galaxies that occurred before today, but not after today. So we can watch them for billions of years more before they “disappear”.

The expansion of space does not cause expansion of matter. Unlike atoms, people, and planets, photons are not coherent objects whose size has been determined by a compromise among forces. So, photons expand, but people don’t. (If gravity got stronger, you would shrink to a new equilibrium size; you would not continue to shrink.)

The acceleration of the universe’s expansion exerts a gentle outward force on bodies in the universe, hence they attain a slightly larger equilibrium size: they do not continue to expand (unless the expansion’s acceleration is increasing) [180].

For example, the Earth’s gravity keeps the Earth a constant size regardless of the universe’s expansion.

The decreasing Hubble parameter does not contradict the increasing rate (acceleration) of expansion.

Consider a single galaxy 100 Mpc away, today. So it’s receding at around 7000 km/s, today (assuming \( H_0 = 70 \text{ km/s/Mpc} \)). If the Hubble parameter were constant in time (which it’s not!), then in the future, when this galaxy is 200 Mpc away, it would be receding at 14000 km/s. That would be an accelerating expansion: things speeding up as they move away.

Consider the same galaxy, 100 Mpc away, today—receding at 7000 km/s, today. Let’s say in the future, when this galaxy is 200 Mpc away, it will recede at 13000 km/s. Well, that’s an accelerating expansion, too. However, the Hubble constant is getting smaller in this example.

So it’s okay if the Hubble parameter is getting smaller; it doesn’t mean expansion is slowing down.

180 At Earth’s center, the outward acceleration (from accelerating expansion) is \( \sim 10^{-90} \) of the inward acceleration (from gravity).

Intuitively, it seems like we should see a decreasing rate (deceleration) of expansion due to gravity between superclusters. So what is causing the expansion to accelerate? The cause seems to be unobservable at any wavelength—an property named “dark” in astronomy. But whatever this dark cause is, it’s very energetic—hence the name dark energy.

The acceleration has not been consistent since the big bang. The density of matter obviously decreases as the universe expands. But the density of dark energy is expected to change slowly or not at all as the universe expands. So we expect the young universe was dominated by matter, while the current universe is dominated by dark energy. Hence, the expansion slowed down for the first 9 billion years or so (due to gravity), but has been speeding up since then. [sketch 274]

In 1998, observations of distant (out to \( \sim 4 \times 10^9 \text{ ly} \)) supernovas first indicated the expansion is accelerating. How can supernovas indicate this? Consider the following logical steps.

1. Brightness and redshift, \( z \), are measured for distant supernovas.

2. Low brightness shows that each supernova is fainter than expected.

3. Therefore each supernova must have been more distant than expected (when it emitted the light we see today).

4. Therefore the light from the supernova must have taken longer than expected to travel to Earth.

5. Therefore the universe must have taken longer than expected to expand by the factor \( 1 + z \). (The expansion factor, \( 1 + z \), is the ratio of sizes of the universe at two different times. For example, if a galaxy has \( z = 1 \), then the universe has doubled in size during the time the photons were in transit to Earth.)

6. Therefore the universe must have been expanding slower in the past.

7. Therefore the expansion must be accelerating.

Critizims of these conclusions have not been strong

181 (a) Can we trust the relationship between brightness and distance? Yes, intrinsic luminosity of Type Ia Supernovas has been calibrated. (b) Consider two possible astrophysical causes of the extra faintness. First, intergalactic dust could be a cause. Second, supernovas of long ago had a smaller abundance of heavy elements, and could have been intrinsically fainter as a result. If either (or both) of these is the case, then the dimming effects should increase with redshift (increase with distance). But in the early 2000’s, very distant (\( \sim 10^{10} \text{ ly} \)) supernovas were discovered, and their brightness was higher than to be expected if the astrophysical causes were legitimate. (Note that the transition from deceleration to acceleration happened about 5 billion years ago.)

182 An object’s gravity is proportional to its energy density plus three times the pressure. For example, the Sun’s gravity is slightly greater than that of a cold ball of equivalent mass. And a photon gas has pressure equal to 1/3 its energy density, so its gravity is twice that of a cold ball of equivalent (via \( G_{\mu\nu} = \kappa T_{\mu\nu} \)) mass.

Dark energy has negative pressure (like a stretched elastic sheet). If the pressure is less than \(-1/3\) times the energy density, then the sum of energy
8.13 Fate of the Universe

- prerequisite: Cosmic Horizon & Dark Energy

- The fate of the universe involves the question of how the universe will expand in the distant future. For example, will the universe expand forever?

The simplest models in relativistic cosmology are the Friedmann models. They involve the curvature, \(k\), of the universe and the cosmological constant, \(\Lambda\).

- Consider a comparison of possible \(k\) values, i.e., geometries; different geometries can mean different fates. Imagine two laser beams, which are locally parallel, travelling across billions of light years.

  - They might intersect (converge). [sketch 275] This would imply positive curvature \((k = 1)\); space is spherical. [sketch 276] This is a closed topology.

  - They might remain parallel. [sketch 277] This would imply zero curvature \((k = 0)\); space is flat. [sketch 278] This is an open topology.

  - They might diverge. [sketch 279] This would imply negative curvature \((k = -1)\); space is hyperbolic. [sketches 280 & 281] This is an open topology.

- Consider a comparison of possible \(\Lambda\) values, i.e., universal-cosmological forces; different values can mean different fates. Imagine everything in the universe pushing or pulling on everything else.

  - The cosmological force can be attractive \((\Lambda < 0)\). This always implies an “oscillating model”, in which the expansion eventually halts and the universe begins contracting. Finally it ends in an apocalyptic event known as the “big crunch”.

  - The cosmological force can be non-existent \((\Lambda = 0)\). This can imply an oscillating model, a model that expands forever, or a model in between. (In between? Perhaps like launching a rocket at \(v = v_{exc}\), as opposed to \(v < v_{exc}\) or \(v > v_{exc}\).)

  - The cosmological force can be repulsive \((\Lambda > 0)\). This can imply many different scenarios (including all of those mentioned for other \(\Lambda\) values), depending on how \(\Lambda\) compares to the “critical value”, \(\Lambda_c\). Note that the most readily available interpretation of \(\Lambda > 0\) is dark energy!

- With all the possible values for \(k\) and \(\Lambda\), there are fourteen different Friedmann models: too many to explore in detail.

- Of course, more realistic models of the universe should involve dark matter and dark energy more explicitly. As of 2013, results from the Planck satellite indicate the universe is about 5% normal matter, 27% dark matter, and 68% dark energy.

- Consider the ultimate heat death of the universe.

- Reading.

  - TCPF2: Chapter 14, Section 2, pages 242 - 243.

9 Life in the Universe

9.1 Interstellar Chemistry

- prerequisite: Cosmic Recycling

- Some massive stars, late in their evolution, send off much wind. The wind is made of silicates (Si, Mg, Fe, & O), among other constituents.

As the silicates move away from the star and cool, they condense into tiny grains.

- Consider the relative cosmic abundances of the five most common elements, relative to \(\text{H}^{189}\). Note that He is inert; it doesn’t react with other elements. (That is, it can’t play an important role in life or the formation of life because if it can’t be part of a molecule, then it certainly can’t be part of anything more complicated than a molecule.)

<table>
<thead>
<tr>
<th>element</th>
<th>relative abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>10,000</td>
</tr>
<tr>
<td>He</td>
<td>790</td>
</tr>
<tr>
<td>O</td>
<td>8</td>
</tr>
<tr>
<td>C</td>
<td>5</td>
</tr>
<tr>
<td>N</td>
<td>1</td>
</tr>
<tr>
<td>all others</td>
<td>2%</td>
</tr>
</tbody>
</table>

- Silicate grains react with cosmic materials. They do so through surface chemistry instead of gas-phase chemistry.

\(188\) The latter two correspond to expansion proportional to \(t\) asymptotically and expansion proportional to \(t^{2/3}\).

\(187\) Some of the more popular models have special names: Einstein static, de Sitter, Eddington-Lemaître, Lemaître, Einstein-de Sitter, oscillating, indefinitely expanding, etc.

\(188\) WU 170 1-5 (12)

\(189\) A few other elements are about as common as N, but they’re not so relevant for forming life.
Imagine two molecules bouncing around a completely empty (vacuum), room-size box. [sketch 282] What are the odds they will collide with each other and react with each other? (This is like gas-phase chemistry.) On the other hand, imagine this box also contains a table with a very special surface. When either molecule strikes such a surface, it sticks to the surface and rolls around on it. [sketch 283] What are the odds the two molecules will end up rolling around on the surface and then collide with each other and then react? (This is like surface chemistry.)

It seems amazing, but the surfaces of interstellar silicate grains behave just this way. So when atoms run into a grain (those most likely to do so are, of course, the elements H, O, C, & N), they stick to the grain, roll around its surface, and then react with each other.

- What sort of molecules would we expect to form on the grain surface? Well, let’s think about it. If the most abundant element, H, is combined with the second-most abundant reactive element, O, then H₂O (water) is formed. If H is combined with C then CH₄ (methane) is formed. And if H is combined with N then NH₃ (ammonia) is formed. These three molecules are the most common molecules (after H₂, molecular hydrogen) in the universe. There are many interesting, yet simple, molecules that can be formed. Others include CO (carbon monoxide), CN (cyanide), and so on. So the silicate grains form simple organic mantles. [sketch 284]

But we are surely forgetting something: the most abundant particle in the universe. What is it? Light! Realistically, we must include photons in this mix; we must consider photochemistry. When similar grains (silicate core with simple organic mantle) are made in a laboratory, they are subsequently exposed to UV radiation – similar to what they would receive in space from nearby stars. The results are interesting, including (NH₂)₂CO (urea), NH₂CH₂COOH (glycine, the simplest amino acid), and so on. So a typical grain cruising around interstellar space has a somewhat complex, organic surface. [sketch 285]

- Our exploration of interstellar chemistry so far has several intriguing ideas. But one of the main ingredients of science is that it can be tested, either by experiment or by observation. So we must ask. Is there observational evidence to support these ideas? The answer is yes. The following constitutes a small fraction of the organic molecules that have been observed in comets: CO₂ (carbon dioxide), HCN (hydrogen cyanide, used in the gas chamber), H₂CO (formaldehyde, used to preserve bodies for dissection) CH₃OH (methyl alcohol, a.k.a. methanol), and even CH₃CH₂COOH (glycine, the simplest amino acid) [197]

Comets have an aggregate structure, meaning they are light and “fluffy” like popcorn.

- Comets have bombarded the Earth at least hundreds of times. The water for at least half of the Earth’s oceans was brought by comets. (Note that comets are made mostly of water.) Given the amount of biomass in one comet, it’s easily possible that all of the Earth’s biomass was delivered by comets [199]

We expect that some of the organic molecules could be destroyed during the impact (which is very energetic), but not all of them.

- Some of the organic material actually survived the impact. We expect this to some degree through the combination of aggregate structure of comets with the early Earth’s atmosphere having been much thicker than it is today.

In 2012, J. G. Blank performed experiments demonstrating that “the building blocks of life could, indeed, have remained unaltered until now.”

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190 Oxygen forms two bonds.
191 Carbon forms four bonds.
192 Nitrogen forms three bonds.
193 Also of note are HOCH₂CH(OH)CO₂H (glyceraldehyde) and HOCH₂CH(OH)CONH₂ (glyceramide), which exhibit prebiotic mirror symmetry.
194 There are well over 100 molecular species that have been observed in the ISM.

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195 In a previous section, Spectral Lines, we discussed spectra produced by electrons jumping downward: electronic spectra, which tend to be in the visible and UV spectral bands. Most interstellar molecules are observed with rotational spectra, which tend to be in the radio and microwave spectral bands, or observed with vibrational spectra, which tend to be in the IR spectral band.

196 There are well over 100 molecular species that have been observed in comets.
197 Glycine was found in Comet Wild 2 by the Stardust Mission/NASA in 2009.
198 This is a term referring to the total mass of the molecules that can be used for the construction of living organisms.
199 A single comet the size of Comet Hale-Bopp could deliver eighty times the biomass of all the living organisms on our planet.
200 Up to twenty times thicker, and mostly CO₂.
intact despite the tremendous shock wave and other violent conditions in a comet impact.”

• So comets could give a head start to the formation of life. Amino acids may or may not have taken a billion years or more to form in the ISM, but as soon as our solar system formed, these amino acids – the building blocks of life – were delivered, intact, to the surface of the Earth. The Earth didn’t have to wait a billion years or more for amino acids to actually form on its surface.

• Taken together, this is a set of processes probably taking place all over the galaxy and all over the universe. Interstellar chemistry is ubiquitous. Comet formation and bombardment is likely common to all star systems with planets. It’s entirely plausible that the building blocks of life have been, and are being, delivered to planets throughout the galaxy and even the universe. 201

• Homework.

1. (10 points) Trace part of the life of a proton. Begin with it floating in an interstellar cloud. Follow it until it winds up in your heart.

9.3 Search for Extrasolar Planets

• prerequisite: Star Formation in Brief

• Long before extrasolar planets (a.k.a. exoplanets, those around stars other than our Sun) were detected, they were thought to exist as a result of the star formation process. While not all stars were thought to have planets, it was expected that roughly one third would. 202 The first exoplanet was found in 1992. As of 2019, more than 3,700 exoplanets have been found.

• The detection involves a very slight “wobble” in the star that the exoplanet is orbiting. That is, the star’s center of mass is “orbiting” around the center of mass of the “star-planet system”. 203 The technique involves Doppler-shifted spectral lines. 204

• Reading.

  – TCPF2: Chapter 7, Section 1, pages 114 - 119.

9.4 Origin of Life

• prerequisite: Comets

• Oxygen destroys organic molecules, so a cell membrane is needed for protection. But the early Earth had a predominantly CO2 atmosphere, so organic chemistry worked okay (with sunlight). 205 However, such chemistry might not produce enough biomass on its own. Fortunately, comets and asteroids are included as sources of organic molecules on Earth. There is also deep-sea vent chemistry.

When all three sources (atmosphere, comets/asteroids, & deep-sea vents) are taken together, there is plenty of biomass produced.

• The transition from chemistry to biology is of great interest to astrobiologists.

  – Whence came the first self-replicating molecule? (DNA is too complex to start with.) The most obvious candidate is RNA. (But RNA and enzymes can’t replicate without each other.)

  – Consider a molecular analog to natural selection. 206

    Consider a group of simple molecular species, named after letters of the alphabet: A, B, ..., S. Some of the molecules are built from others. For example, A+B=C. How might competition, and therefore natural selection, arise between molecules? Consider a competition between molecules named R and S.

      * A+B=C and D+E=F. Then C+F=S. S is self-replicating.


      * Since S is constructed more easily, it could occur more often. But if it occurs more often, then it will end up “stealing” all of the A molecules. Subsequently, R will not be able to form.

  – Free-floating RNA bases (a.k.a. nucleotides) use minerals on clay as surfaces for surface chemistry. (Remember a previous section, Interstellar Chemistry, in which surface chemistry was found to be relatively efficient.) Hence, RNA bases combine to form RNA strands (up to nearly 100 bases long) in the laboratory.

  – Base-pairing rules then build complementary strands, which then serve as templates for copying (again via base-pairing rules) the original RNA strands. 207

• Confining organic molecules with a pre-cell does two things. First, it keeps the molecules closer together, thereby making chemical reactions more probable. Second, it facilitates a molecular analog to natural selection between RNA molecules (tougher competition).

  – When a warm-water solution of amino acids is cooled, the amino acids can form bonds among themselves to make an enclosed, spherical structure. These are not alive, but...

    * They can grow in size by absorbing more short amino-acid chains until they reach an unstable size at which they split to form “daughter spheres”.

    * They can selectively allow some types of molecules to cross into or out of the enclosure.

    * Some even store energy as electrical voltage across their surfaces, discharging to facilitate chemical reactions inside.

  – The second type of membrane forms spontaneously when lipids are mixed with water.

• Natural selection among RNA molecules in pre-cells leads to complexity 208 which leads to life.

201 WU 180 2-5 (13’)
202 This is because it was estimated that roughly half of the “points of light” in the night sky are binary stars or multiple stars.
203 In the famous Miller-Urey experiment, there were some faulty assumptions about the Earth’s early atmosphere: too much CH4 & NH3, and too little CO2.
204 This is one of the two main components of evolution; the other is mutation. Consider simple examples like the moths in England during the industrial revolution or why humans have tailbones but no tails. (We might consider positive, negative, and neutral evolutionary pressures.)
205 How complex can a molecular-biological system be? Check out Drew Barry’s TED talk: Animations of unseen biology.
9.5 Nature of Life

- prerequisite: Origin of Life

- A cell is a tiny chemical factory that makes reactions more rapid, thereby helping simple molecules become complex.

Cells are carbon-based.

- Carbon forms from one to four bonds. This versatility leads to complexity.
- In comparison, silicon is less abundant, it has weaker bonds, it doesn’t usually form double bonds, and complex Si-based molecules cannot exist long in water.

Cells have four main molecular components: carbohydrates, lipids, proteins, and nucleic acids.

- Carbohydrates provide energy to cells and they play an important structural role.
- Lipids form membranes.
- Proteins are built from long chains of amino acids. Some are enzymes, which are catalysts that greatly accelerate chemical reactions.
- Nucleic acids allow cells to function according to precise, heritable instructions.

Cells come in two types: prokaryotic and eukaryotic.

- Prokaryotic cells have no nucleus, they are simple & small, they constitute more biomass on Earth, they don’t depend on eukaryotes, and they give rise to two domains: bacteria and archaea.
- Eukaryotic cells have a nucleus (enclosing DNA), they are complex & large, the constitute less biomass on Earth, they can’t exist without prokaryotes, and they give rise to one domain: eukarya.

- Metabolism is biochemical manufacturing, which requires raw materials (C, etc.) and energy (to fuel metabolic processes of manufacture).

Storage and release of energy in any living cell happens with the following reactions:

\[ \text{ADP + phosphate group + energy} \rightarrow \text{ATP} \]
\[ \text{ATP} \rightarrow \text{ADP + phosphate group + energy} \]

- Organisms can acquire raw materials either from food or from the atmosphere: heterotrophs or autotrophs, respectively.

Organisms can acquire energy either from food (or inorganic chemicals) or from the Sun: prefixes chemo- or photo-, respectively.

- Water plays a prominent role. Chemicals dissolve in it, so they’re ready to react. It transports chemicals in and waste out. It is part of many reactions, like ATP.
- Consider tardigrades.
- Reading.

- TCPF2: Chapter 15, Section 1, pages 251 - 253.

9.6 Definitions

- The word “extraterrestrial” means nothing more than “outside the Earth”. For example, the Moon is extraterrestrial.
- What are the characteristics of life? Can we define life? We would like a definition of life that is not circular. For example, we can’t define life in any way related to death if death is defined as the end of life. We would like a definition that is unique. How do we go about finding such a definition? One way is to consider necessary & sufficient conditions.

- If no A, then no B. Here A is necessary in order for B to happen. Can we find an A that allows us to make the following statement? “If it doesn’t have A, it’s not alive.” The answer is yes, and there are many examples, one of which is metabolism. If it doesn’t metabolize, it’s not alive. So metabolism is a necessary condition for life. (What about a virus?) In contrast, consider emotions. Is the following statement true? “If it’s not emotional, it’s not alive.” The answer is no. Clearly, mushrooms are not emotional, yet they are alive. So emotions are not a necessary condition for life.

- If A, then B. Here A is sufficient in order for B to happen. Can we find an A that allows us to make the following statement? “If it has A, it’s alive.” The answer is yes, and there are many examples, one of which is metabolism. If it metabolizes, it’s alive. (What about a virus?) Some are enzymes, which are catalysts that greatly accelerate chemical reactions. Some are enzymes, which are catalysts that greatly accelerate chemical reactions. So metabolism is a sufficient condition for life.

In contrast, consider metabolism. Is the following statement true? “If it metabolizes, it’s alive.” The answer is no. Clearly, factories metabolize, yet they’re not alive. (A factory uses raw materials and energy to manufacture.) So metabolism is not a sufficient condition for life.

Ideally, we want a condition that is both necessary and sufficient. The challenge is to think of one. If we could, then we would have life defined.
• We can play the same game of necessary and sufficient conditions for intelligence. Can intelligence be defined?

• So we find that we cannot define life. And we cannot define intelligence. This established, we can still agree to proceed with the discussion. We can still consider, without stumbling over the lack of exact definitions, concepts related to the possible existence of extraterrestrial life and extrasolar intelligence.

• Reading.
  – TCPF2: Chapter 15, Section 1, pages 253 - 254.

• Homework.

1. (8 points) Consider two attempts to define human. In each case, state whether the phrase is (i) necessary, (ii) sufficient, (iii) both, or (iv) neither. (a) Has two hands and two feet. (b) Born of a human. Justify your answers

2. (8 points) Consider two attempts to define human. In each case, state whether the phrase is (i) necessary, (ii) sufficient, (iii) both, or (iv) neither. (a) Thinks logically. (b) Writes poetry. Justify your answers

9.7 Possible Existence of Extrasolar Intelligence

• prerequisite: Nature of Life

• prerequisite: Definitions

• The Drake equation is used to help us organize our thoughts about the possible existence of extrasolar intelligence. And while it provides a quantitative answer, this answer is not meant to be reliable in any way. It can’t be reliable because most of the values in the Drake equation are completely unknown.

• The equation is currently written as

\[ N = R_* f_p n_e f_i f_c f_L. \]

- \( N \) is the number of transmitting civilizations in our Galaxy.
- \( R_* \) is the galactic birthrate of stars per year suitable for hosting life.
- \( f_p \) is the fraction of such stars having planets.
- \( n_e \) is the number of planets and/or moons per star system that have an environment favorable for life.
- \( f_c \) is the fraction of such planets and/or moons on which life has developed.
- \( f_i \) is the fraction of inhabited worlds on which intelligence has developed.
- \( f_c \) is the fraction of “intelligent planets” that produce a civilization capable of interstellar communication.
- \( L \) is the lifetime that such civilizations are broadcasting signals.

If we consider the units of the equation, we find the following.

\[ \text{# of t.c.} = \left( \frac{\text{yr}}{\text{yr}} \right) \left( \frac{\text{yr}}{\text{yr}} \right) \left( \frac{\text{yr}}{\text{yr}} \right) \left( \frac{\text{yr}}{\text{yr}} \right). \]

Hence, we see all the units on the right hand side cancel except the number of transmitting civilizations.

• Estimate.

• Reading.
  – TCPF2: Chapter 15, Section 2, pages 255 - 259.

• Homework.

1. (15 points) What are your personal estimates for the terms in the Drake equation? Why? What total number results (i.e., multiply your terms together) from your estimates? (Beware, most terms are between 0 and 1.)

9.8 Search for Extraterrestrial Intelligence

• prerequisite: Possible Existence of Extraterrestrial Intelligence

• Whenever the search for extraterrestrial intelligence (a.k.a. SETI) is considered, anthropocentrism must be considered with it. That is, one must not assume any processes in the universe are at all affected by the human race; the universe doesn’t “revolve” around us.

• There are at least three options for possible communication with an extraterrestrial civilization. Efficiency and practicality vary widely among the options.

  - A round trip for a small space craft to the nearest star at 70% of the speed of light (an eleven-year time frame) would cost $50 trillion and use the same amount of power that the USA would use in 100,000 years. A similar trip to the center of our Galaxy would cost and use 10,000 times as much.
  - To send a single electron to the nearest star and back in an eighty-year time frame at 10% of the speed of light would require very little energy: about \(10^{16}\) J. However, compare this with a photon.
  - To send a single radio photon, which automatically travels at speed \(c\), to the nearest star and back would only take about eight years, and it would require only one billionth as much energy as the electron previously considered. A standard 100-W bulb uses about \(10^{27}\) times as much energy in an hour.

The photon is the obvious choice to begin with. (Is this choice anthropocentric?)

• Once the decision for a photon is made, the spectral band must be chosen. It’s best to choose a spectral band that isn’t noisy\(^{\text{[210]}}\) so that the signal will stand out against the background.

\(^{\text{[210]}}\) For example, getting a distant person’s attention when surrounded by loud voices and music can be a challenge. Yelling doesn’t help because it just blends in with the noise. There is at least one thing that stands out against the noise: broken glass.
The visible, UV, x-ray, & γ-ray spectral bands are attenuated by interstellar dust clouds. So these frequencies cannot travel well across a galaxy. This leaves the radio, microwave, & IR spectral bands. Check out APoD; image search “milky way”.

- **Within these three spectral bands, there are at least four sources of noise: the universe, the Galaxy, the quantum limit, and the Earth’s atmosphere.** [sketch 289]
  - The universe is noisy at frequencies below about 100 GHz as a result of the cosmic microwave background radiation from the big bang.
  - Our Galaxy is noisy at frequencies below about 2 GHz as a result of synchrotron radiation, which is produced when electrons spiral around the galactic \( \vec{B} \). This eliminates the the low-frequency side of the radio spectral band.
  - The quantum limit gives rise to radio receiver noise at frequencies above about 12 GHz as a result of the uncertainty principle, which describes one of the fundamental properties of the universe. This eliminates the IR spectral band.
  - The Earth’s atmosphere is noisy at frequencies between about 5 and 300 GHz, as a result of water vapor and oxygen in the air. Note that of the four sources, this is the only one that is anthropocentric.

So we are left with a frequency range roughly from 1 to 5 GHz. This is in the microwave and the high-frequency radio spectral bands.

- **This spectral region still contains many (at least billions) of possible frequencies. Is there a way to choose just one?** As it happens, there is sort of a “magic frequency” in this range: 1.42 GHz. It’s “magic” because it is one of the most well-known frequencies to anyone with knowledge of basic atomic physics and spectroscopy.

This radio photon is produced as a result of the “H spin flip”[^212] when the electron’s spin transitions from parallel to antiparallel relative to the proton’s spin. [sketch 290]

Not all astronomers agree on the 1.42 GHz. Should we expect an extraterrestrial civilization to agree on it?

- **Communication involves transmitting and receiving information. It’s much easier to receive than transmit since it requires so much less energy. On Earth, the SETI Project is hoping to receive radio signals. The very simplest message that can be sent or received is “I am here.”[^213] All that is required is the reception of a signal that stands out against the background noise in such a way that there is no ambiguity – a signal that must have been artificially generated.**

- **Consider a series of ones and zeros, in which the ones represent signal pulses and the zeros represent pauses between the pulses. What if a few strong signals are expected, the choice is smaller diameter and shorter exposure times. If many weak signals are expected, the choice is larger diameter and longer exposure times.** But there’s no way to know what to expect!

- **With the SETI Project, the “trade-offs” must be accepted. A large-diameter telescope will detect faint signals, but it will limit the number of directions observed at any given time.**[^214] A long exposure time will detect faint signals, but it will limit the number of directions you can observe over an extended period of time. [sketch 291]

If a few strong signals are expected, the choice is smaller diameter and shorter exposure times. If many weak signals are expected, the choice is larger diameter and longer exposure times. But there’s no way to know what to expect!

- **Reading.**
  - TCPF2: Chapter 15, Section 2, pages 259 - 261.

10 Miscellaneous

10.1 Pseudoscience

- **Just for fun, we may consider pseudoscience associated with Stonehenge, the Pyramids of Giza, the Nazca lines, the “face” on Mars (or a tortilla), the Loch Ness monster, Bigfoot, the Bermuda triangle, crop circles, alien abductions, or any other suggestions.**

[^212]: This is just like using binoculars. Without the binoculars, your eyes see many directions at once: almost everything in front of you. With binoculars, you can clearly see objects much farther away, but you only see a tiny fraction of the things in front of you.

[^213]: A pulsar is a type of neutron star that sends synchrotron radiation in the direction of Earth. The signal comes in the form very regularly-spaced pulses of radiation. As a joke, before the cause was understood, they were nicknamed LGM’s, which stands for “little green men.”

[^214]: This is like taking photos at night. You have to use your camera’s mode that leaves the shutter open for a long time. But this means you can’t take as many photos in an hour.
10.2 Exam Instructions & Answer Sheet

- 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. There are multiple “written” questions, worth several points each, the answers of which are to be legibly written on your scantron form, 886-E.

  - Your name is required on three items: scantron, answer page, and exam. All three items must be turned in. When you are finished with the exam, place your exam and your answer sheet inside your scantron.

  - For each numbered blank, choose the most appropriate answer from the alphabetized list on the answer page. If none are appropriate, choose “de. none of the above”. Some of the answers may be used more than once; many of the answers won’t 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 blanks, not the letters that fill in the scantron boxes.
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