Chapter S4
Building Blocks of the Universe

Agenda

• Announce:
  – Pass back “Waves on a String” “Parallax I”
• Errors vs Uncertainty
• deGrasse Tyson
• Review Ch. 11—Jovian Planets
• Ch. S4—Building Blocks

Errors vs Uncertainty

• Uncertainty & Error:
  – Always present to some degree
  – “Better” equipment/design can help make small
• Uncertainty:
  – Allowance for inherent inability to measure exactly
• Error:
  – Real world phenomena which you know are there, you cannot eliminate, but which you cannot account for
  – Examples: friction, wind resistance, imperfect weighting of dice,

Leonids

• Night

About how long does it take a spacecraft to go from Earth to Jupiter?

• A week
• A month
• A year
• Several years
• Several decades
<table>
<thead>
<tr>
<th>Question</th>
<th>Options</th>
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</table>
| About how long does it take a spacecraft to go from Earth to Jupiter?   | • A week  
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| What are the most common *elements* in the atmospheres of the Jovian Planets? | • Water  
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• Oxygen and nitrogen  
• Oxygen and carbon  
• None of the above                                                      |
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• Water and Carbon Dioxide \((CO_2)\)  
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• None of the above                                                     |
| Since there are a lot of flammable gases on Jupiter, such as methane and propane, if you lit a match, would Jupiter burn? | • Yes  
• No                                      |
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• Yes
• No – because there is no free oxygen

Convection circulates gasses from deep in Jupiter's atmosphere to the top, where they

• Escape into space
• Condense and make rain
• Condense and make clouds
• Form compounds

Jupiter does not have a large metal core like the Earth. How can it have a magnetic field?

• The magnetic field is left over from when Jupiter accreted
• Its magnetic field comes from the Sun
• It has metallic hydrogen inside, which circulates and makes a magnetic field
• That’s why its magnetic field is weak

Auroras (called Northern Lights in the United States):

• Are found on Earth
• Are found on Jupiter
• Indicate a magnetic field is present
• Result when particles in the solar wind hit a planet
• All of the above
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Jupiter is about three times as massive as Saturn, but only slightly larger. Why?
- It is made of stronger material
- It is made of weaker material
- Adding mass increases gravity and compresses gasses
- Because they are made of different gasses
- None of the above

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- Earth—due to its earthquakes and volcanoes
- Mercury, the hottest planet
- Mars
- Jupiter
- Jupiter’s moon Io

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How does Io get heated by Jupiter?
- Auroras
- Light
- Infrared radiation
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- Chemical reactions
- Friction due to its fast rotation
- Shrinking and releasing gravitational potential energy
- Tidal forces

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What shape are moons?
- Spherical
- Large ones are spherical, small ones irregular
- It depends on which planet they orbit.
- Earth and Jupiter’s moons are spherical, Uranus and Neptune’s are not

Why can icy moons be geologically active when a planet the same size would be geologically “dead?”
- Planets are older - some cooled and died.
- Ice melts at a lower temperature than rock, making flows and activity easier
- Many have tidal heating caused by their planet
- All of the above
- #2 and #3
Why can icy moons be geologically active when a planet the same size would be geologically “dead?”

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- All of the above.
  - #2 and #3.

Why do Jupiter, Saturn, Uranus, and Neptune all have rings?

- Rings were left over from solar system formation.
- They all captured particles.
- All four planets had a large moon that disintegrated.
- All have small moons and small orbiting particles that constantly collide and make rings.

Surprising discovery? - Saturn’s core is pockmarked with impact craters and dotted with volcanoes erupting basaltic lava.

1. Plausible. Saturn’s moons also show impact craters and volcanoes.
2. Plausible. Saturn’s atmosphere originated from the volatiles in impactors that were released via volcanic activity.
3. Implausible. No impactors would survive the immense pressures at the depth of Saturn’s core.
4. Implausible. Any large impactor approaching Saturn would be broken up by tidal forces.
5. Implausible. Saturn’s high rotation would prevent an impactor from reaching its core.

S4.1 The Quantum Revolution

- Our goals for learning.
- How has the quantum revolution changed our world?
How has the quantum revolution changed our world?

The Quantum Realm
- Light behaves like particles (photons)
- Atoms consist mostly of empty space
- Electrons in atoms are restricted to particular energies
- The science of this realm is known as quantum mechanics

Surprising Quantum Ideas
- Protons and neutrons are not truly fundamental—they are made of quarks
- Antimatter can annihilate matter and produce pure energy
- Just four forces govern all interactions: gravity, electromagnetic, strong, and weak
- Particles can behave like waves
- Quantum laws have astronomical consequences

Quantum Mechanics and Society
- Understanding of quantum laws made possible our high-tech society:
  - Radios and television
  - Cell phones
  - Computers
  - Internet

What have we learned?
- How has the quantum revolution changed our world?
  - Quantum mechanics has revolutionized our understanding of particles and forces and made possible the development of modern electronic devices

S4.2 Fundamental Particles and Forces
- Our goals for learning
  - What are the basic properties of subatomic particles?
  - What are the fundamental building blocks of matter?
  - What are the fundamental forces in nature?
What are the basic properties of subatomic particles?

Properties of Particles

- Mass
- Charge (proton +1, electron -1)
- Spin
  - Each type of subatomic particle has a certain amount of angular momentum, as if it were spinning on its axis

Fermions and Bosons

- Physicists classify particles into two basic types, depending on their spin (measured in units of $\hbar/2\pi$)
  - Fermions have half-integer spin (1/2, 3/2, 5/2, ...)
    - Electrons, protons, neutrons
  - Bosons have integer spin (0, 1, 2, ...)
    - Photons

Fundamental Particles

Orientation of Spin

- Fermions with spin of 1/2 have two basic spin states: up and down
What are the fundamental building blocks of matter?

Quarks

- Protons and neutrons are made of quarks
- *Up quark* (u) has charge +2/3
- *Down quark* (d) has charge -1/3

Quarks and Leptons

- Six types of quarks: up, down, strange, charmed, top, and bottom
- Leptons are not made of quarks and also come in six types
  - Electron, muon, tauon
  - Electron neutrino, mu neutrino, tau neutrino
- Neutrinos are very light and uncharged

Matter and Antimatter

- Each particle has an antimatter counterpart
- When a particle collides with its antimatter counterpart, they annihilate and become pure energy in accord with \( E = mc^2 \)

Matter and Antimatter

- Energy of two photons can combine to create a particle and its antimatter counterpart (pair production)

What are the fundamental forces in nature?
Four Forces

• Strong Force (holds nuclei together)
  – Exchange particle: gluons
• Electromagnetic Force (holds electrons in atoms)
  – Exchange particle: photons
• Weak force (mediates nuclear reactions)
  – Exchange particle: weak bosons
• Gravity (holds large-scale structures together)
  – Exchange particle: gravitons

Strength of Forces

• Inside nucleus:
  – strong force is $100$ times electromagnetic
  – weak force is $10^{-5}$ times electromagnetic force
  – gravity is $10^{-43}$ times electromagnetic
• Outside nucleus:
  – Strong and weak forces are unimportant

What have we learned?

• What are the basic properties of subatomic particles?
  – Charge, mass, and spin
• What are the fundamental building blocks of matter?
  – Quarks (up, down, strange, charmed, top, bottom)
  – Leptons (electron, muon, tauon, neutrinos)
• What are the fundamental forces in nature?
  – Strong, electromagnetic, weak, gravity

S4.3 Uncertainty and Exclusion in the Quantum Realm

• Our goals for learning
• What is the uncertainty principle?
• What is the exclusion principle?

What is the uncertainty principle?

Uncertainty Principle

• The more we know about where a particle is located, the less we can know about its momentum, and conversely, the more we know about its momentum, the less we can know about its location
Position of a Particle

- In our everyday experience, a particle has a well-defined position at each moment in time.
- But in the quantum realm particles do not have well-defined positions.

Electrons in Atoms

- In quantum mechanics an electron in an atom does not orbit in the usual sense.
- We can know only the probability of finding an electron at a particular spot.

Electron Waves

- On atomic scales, an electron often behaves more like a wave with a well-defined momentum but a poorly defined position.

Location and Momentum

\[
\text{Uncertainty in location} \times \text{Uncertainty in location} = \text{Planck's Constant (h)}
\]

Energy and Time

\[
\text{Uncertainty in energy} \times \text{Uncertainty in time} = \text{Planck's Constant (h)}
\]

What is the exclusion principle?
Quantum States

• The quantum state of a particle specifies its location, momentum, orbital angular momentum, and spin to the extent allowed by the uncertainty principle.

Exclusion Principle

• Two fermions of the same type cannot occupy the same quantum state at the same time.

Exclusion in Atoms

• Two electrons, one with spin up and the other with spin down, can occupy a single energy level.

• A third electron must go into another energy level.

What have we learned?

• What is the uncertainty principle?
  – We cannot simultaneously know the precise value of both a particle’s position and its momentum.
  – We cannot simultaneously know the precise value of both a particle’s energy and the time that it has that energy.

• What is the exclusion principle?
  – Two fermions cannot occupy the same quantum state at the same time.

S4.4 The Quantum Revolution

• Our goals for learning
  • How do the quantum laws affect special types of stars?
  • How is “quantum tunneling” crucial to life on Earth?
  • How empty is empty space?
  • Do black holes last forever?

How do the quantum laws affect special types of stars?
Thermal Pressure

- Molecules striking the walls of a balloon apply \textit{thermal pressure} that depends on the temperature inside the balloon
- Most stars are supported by thermal pressure

Degeneracy Pressure

- Laws of quantum mechanics create a different form of pressure known as \textit{degeneracy pressure}
- Squeezing matter restricts locations of its particles, increasing their uncertainty in momentum
- But two particles cannot be in the same quantum state (including momentum) at the same time
- There must be an effect that limits how much matter can be compressed—\textit{degeneracy pressure}

Auditorium Analogy

- When the number of quantum states (chairs) is much greater than the number of particles (people), it’s easy to squeeze them into a smaller space

Auditorium Analogy

- When the number of quantum states (chairs) is nearly the same as the number of particles (people), it’s hard to squeeze them into a smaller space

Degeneracy Pressure in Stars

- \textit{Electron degeneracy pressure} is what supports white dwarfs against gravity—quantum laws prevent its electrons from being squeezed into a smaller space
- \textit{Neutron degeneracy pressure} is what supports neutron stars against gravity—quantum laws prevent its neutrons from being squeezed into a smaller space

How is “quantum tunneling” crucial to life on Earth?
Quantum Tunneling

- Person in jail does not have enough energy to crash through the barrier.
- Uncertainty principle allows subatomic particle to “tunnel” through barriers because of uncertainty in energy.

Quantum Tunneling and Life

- At the core temperature of the Sun, protons do not have enough energy to get close enough to other protons for fusion (electromagnetic repulsion is too strong).
- Quantum tunneling saves the day by allowing protons to tunnel through the electromagnetic energy barrier.

How empty is empty space?

Virtual Particles

- Uncertainty principle (in energy & time) allows production of matter-antimatter particle pairs.
- But particles must annihilate in an undetectably short period of time.

Vacuum Energy

- According to quantum mechanics, empty space (a vacuum) is actually full of virtual particle pairs popping in and out of existence.
- The combined energy of these pairs is called the vacuum energy.

Do black holes last forever?
Virtual Particles near Black Holes

- Particles can be produced near black holes if one member of a virtual pair falls into the black hole.
- Energy to permanently create other particle comes out of black hole’s mass.

Hawking Radiation

- Stephen Hawking predicted that this form of particle production would cause black holes to “evaporate” over extremely long time periods.
- Only photons and subatomic particles would be left.

What have we learned?

- How do the quantum laws affect special types of stars?
  - Quantum laws produce degeneracy pressure that supports white dwarfs and neutron stars.
- How is “quantum tunneling” crucial to life on Earth?
  - Uncertainty in energy allows for quantum tunneling through which fusion happens in Sun.

What have we learned?

- How empty is empty space?
  - According to quantum laws, virtual pairs of particles can pop into existence as long as the annihilate in an undetectably short time period.
  - Empty space should be filled with virtual particles whose combined energy is the vacuum energy.
- Do black holes last forever?
  - According to Stephen Hawking, production of virtual particles near a black hole will eventually cause it to “evaporate.”