Chapter 4

Making Sense of the Universe:

Understanding Motion, Energy, and Gravity

Johannes Kepler (1571-1630)

• Kepler first tried to match the planet orbital observations with circular orbits

• But an 8-arcminute discrepancy led him eventually to ellipses…

"If I had believed that we could ignore these eight minutes [of arc], I would have patched up my hypothesis accordingly. But, since it was not permissible to ignore, those eight minutes pointed the road to a complete reformation in astronomy."

Kepler's First Law: The orbit of each planet around the Sun is an *ellipse* with the Sun at one focus.

Kepler's Second Law: As a planet moves around its orbit, it sweeps out equal areas in equal times.

Kepler's Third Law

More distant planets orbit the Sun at slower average speeds, obeying the relationship

$$p^2 = a^3$$

p = orbital period in years

a = avg. distance from Sun in AU

4.1 Describing Motion

Our goals for learning:

- How do we describe motion?
- How is mass different from weight?

How do we describe motion?

Precise definitions to describe motion:

- **Speed**: Rate at which object moves

$$\text{speed} = \frac{\text{distance}}{\text{time}} \quad \left(\text{units of } \frac{\text{m}}{\text{s}}\right)$$

example: speed of 10 m/s

- **Velocity**: Speed and direction
  example: 10 m/s, due east

- **Acceleration**: Any change in velocity
  units of speed/time (m/s^2)

The Acceleration of Gravity

- All falling objects accelerate at the same rate (not counting friction of air resistance).
- On Earth, $g \approx 10$ m/s^2: speed increases 10 m/s with each second of falling.

The Acceleration of Gravity (*g*)

- Galileo showed that *g* is the *same* for all falling objects, regardless of their mass.

Apollo 15 demonstration

Momentum and Force

- Momentum = mass × velocity
- A **net force** changes momentum, which generally means an acceleration (change in velocity)
- Rotational momentum of a spinning or orbiting object is known as **angular momentum**

How is mass different from weight?

- **Mass** – the amount of matter in an object
- **Weight** – the *force* that acts upon an object

You are weightless in free-fall!

Why are astronauts weightless in space?

• There *is* gravity in space
• Weightlessness is due to a constant state of free-fall

What have we learned?

- How do we describe motion?
  - Speed = distance / time
  - Speed & direction => **velocity**
  - Change in velocity => **acceleration**
  - **Momentum** = mass x velocity
  - **Force** causes change in momentum, producing acceleration

What have we learned?

- How is mass different from weight?
  - Mass = quantity of matter
  - Weight = force acting on mass
  - Objects are weightless in free-fall

4.2 Newton’s Laws of Motion

Our goals for learning:

- How did Newton change our view of the universe?
- What are Newton’s three laws of motion?

How did Newton change our view of the universe?

- Realized the same physical laws that operate on Earth also operate in the heavens
  - ⇒ one *universe*
- Discovered laws of motion and gravity
- Much more: Experiments with light; first reflecting telescope, calculus…

Sir Isaac Newton
(1642-1727)

Newton’s first law of motion: An object moves at constant velocity unless a net force acts to change its speed or direction.

Newton’s second law of motion

Force = mass × acceleration

Newton’s third law of motion:

For every force, there is always an *equal and opposite* reaction force.

What have we learned?

- How did Newton change our view of the universe?
  - He discovered laws of motion & gravitation
  - He realized these same laws of physics were identical in the universe and on Earth
- What are Newton's Three Laws of Motion?
  - 1. Object moves at constant velocity if no net force is acting.
  - 2. Force = mass × acceleration
  - 3. For every force there is an equal and opposite reaction force

4.3 Conservation Laws in Astronomy:

Our goals for learning:

- Why do objects move at constant velocity if no force acts on them?
- What keeps a planet rotating and orbiting the Sun?
- Where do objects get their energy?

Conservation of Momentum

- The total momentum of interacting objects cannot change unless an external force is acting on them
- Interacting objects exchange momentum through equal and opposite forces

Conservation of Angular Momentum

angular momentum = mass x velocity x radius

- The angular momentum of an object cannot change unless an external twisting force (torque) is acting on it
- Earth experiences no twisting force as it orbits the Sun, so its rotation and orbit will continue indefinitely

Where do objects get their energy?

- Energy makes matter move.
- Energy is conserved, but it can:
  – Transfer from one object to another
  – Change in form

Basic Types of Energy

- Kinetic (motion)
- Radiative (light)
- Stored or potential

Energy can change type but cannot be destroyed.

Thermal Energy:

the collective kinetic energy of many particles
(for example, in a rock, in air, in water)

Thermal energy is related to temperature but it is NOT the same.
Temperature is the *average* kinetic energy of the many particles in a substance.

Thermal energy is a measure of the total kinetic energy of all the particles in a substance. It therefore depends both on *temperature* AND *density*
Example:

Gravitational Potential Energy

- On Earth, depends on:
  - object's mass (m)
  - strength of gravity (*g*)
  - distance object could potentially fall

Gravitational Potential Energy

- In space, an object or gas cloud has more gravitational energy when it is spread out than when it contracts.

⇒A contracting cloud converts gravitational potential energy to thermal energy.

Mass-Energy

- Mass itself is a form of potential energy

$$E = mc^2$$

- A small amount of mass can release a great deal of energy
- Concentrated energy can spontaneously turn into particles (for example, in particle accelerators)

Conservation of Energy

- Energy can be neither created nor destroyed.
- It can change form or be exchanged between objects.
- The total energy content of the Universe was determined in the Big Bang and remains the same today.

What have we learned?

- Why do objects move at constant velocity if no force acts on them?
  - Conservation of momentum
- What keeps a planet rotating and orbiting the Sun?
  - Conservation of angular momentum
- Where do objects get their energy?
  - Conservation of energy: energy cannot be created or destroyed but only transformed from one type to another.
  - Energy comes in three basic types: kinetic, potential, radiative.

4.4 The Universal Law of Gravitation

Our goals for learning:

- What determines the strength of gravity?
- How does Newton's law of gravity extend Kepler's laws?

What determines the strength of gravity?

The **Universal Law of Gravitation:**

1. Every mass attracts every other mass.
2. Attraction is *directly* proportional to the product of their masses.
3. Attraction is *inversely* proportional to the *square* of the distance between their centers.

How does Newton's law of gravity extend Kepler's laws?

- Kepler's first two laws apply to all orbiting objects, not just planets
- Ellipses are not the only orbital paths. Orbits can be:
  - Bound (ellipses)
  - Unbound
    - Parabola
    - Hyperbola

Center of Mass

- Because of momentum conservation, orbiting objects orbit around their center of mass

Newton and Kepler's Third Law

His laws of gravity and motion showed that the relationship between the *orbital period* and *average orbital distance* of a system tells us the *total mass* of the system.

Examples:

- Earth's orbital period (1 year) and average distance (1 AU) tell us the Sun's mass.
- Orbital period and distance of a satellite from Earth tell us Earth's mass.
- Orbital period and distance of a moon of Jupiter tell us Jupiter's mass.

Newton's Version of Kepler's Third Law

$$p^2 = \frac{4\pi^2}{G(M_1 + M_2)} a^3 \quad \text{OR} \quad M_1 + M_2 = \frac{4\pi^2}{G} \frac{a^3}{p^2}$$

p = orbital period

a=average orbital distance (between centers)

$(M_1 + M_2)$ = sum of object masses

What have we learned?

- What determines the strength of gravity?
  - Directly proportional to the *product* of the masses (M x m)
  - *Inversely* proportional to the *square* of the separation
- How does Newton's law of gravity allow us to extend Kepler's laws?
  - Applies to other objects, not just planets.
  - Includes unbound orbit shapes: parabola, hyperbola
  - Can be used to measure mass of orbiting systems.

4.5 Orbits, Tides, and the Acceleration of Gravity

Our goals for learning:

- How do gravity and energy together allow us to understand orbits?
- How does gravity cause tides?
- Why do all objects fall at the same rate?

How do gravity and energy together allow us to understand orbits?

More gravitational energy;
Less kinetic energy

Less gravitational energy;
More kinetic energy

Total orbital energy stays constant

- Total orbital energy (gravitational + kinetic) stays constant if there is no external force
- Orbits cannot change spontaneously.

Changing an Orbit

⇒ So what can make an object gain or lose orbital energy?

- Friction or atmospheric drag
- A gravitational encounter.

Escape Velocity

- If an object gains enough orbital energy, it may escape (change from a bound to unbound orbit)
- **Escape velocity** from Earth ≈ 11 km/s from sea level (about 40,000 km/hr)

How does gravity cause tides?

- Moon's gravity pulls harder on near side of Earth than on far side
- Difference in Moon's gravitational pull stretches Earth

What have we learned?

- How do gravity and energy together allow us to understand orbits?
  - Change in total energy is needed to change orbit
  - Add enough energy (escape velocity) and object leaves
- How does gravity cause tides?
  - Moon's gravity stretches Earth and its oceans.
- Why do all objects fall at the same rate?
  - Mass of object in Newton's second law exactly cancels mass in law of gravitation.