PHYS12 CH:7 The Force That Shapes Galaxies

From Falling Apples to Orbiting Planets

Mr. Gullo

December 2025

Outline

The Mystery

What do a falling apple and the moon
have in common?

The Mystery

What do a falling apple and the moon
have in common?

The same invisible force governs both...

The Mystery

What do a falling apple and the moon
have in common?

The same invisible force governs both...

Gravity shapes everything.

Kepler and Newton

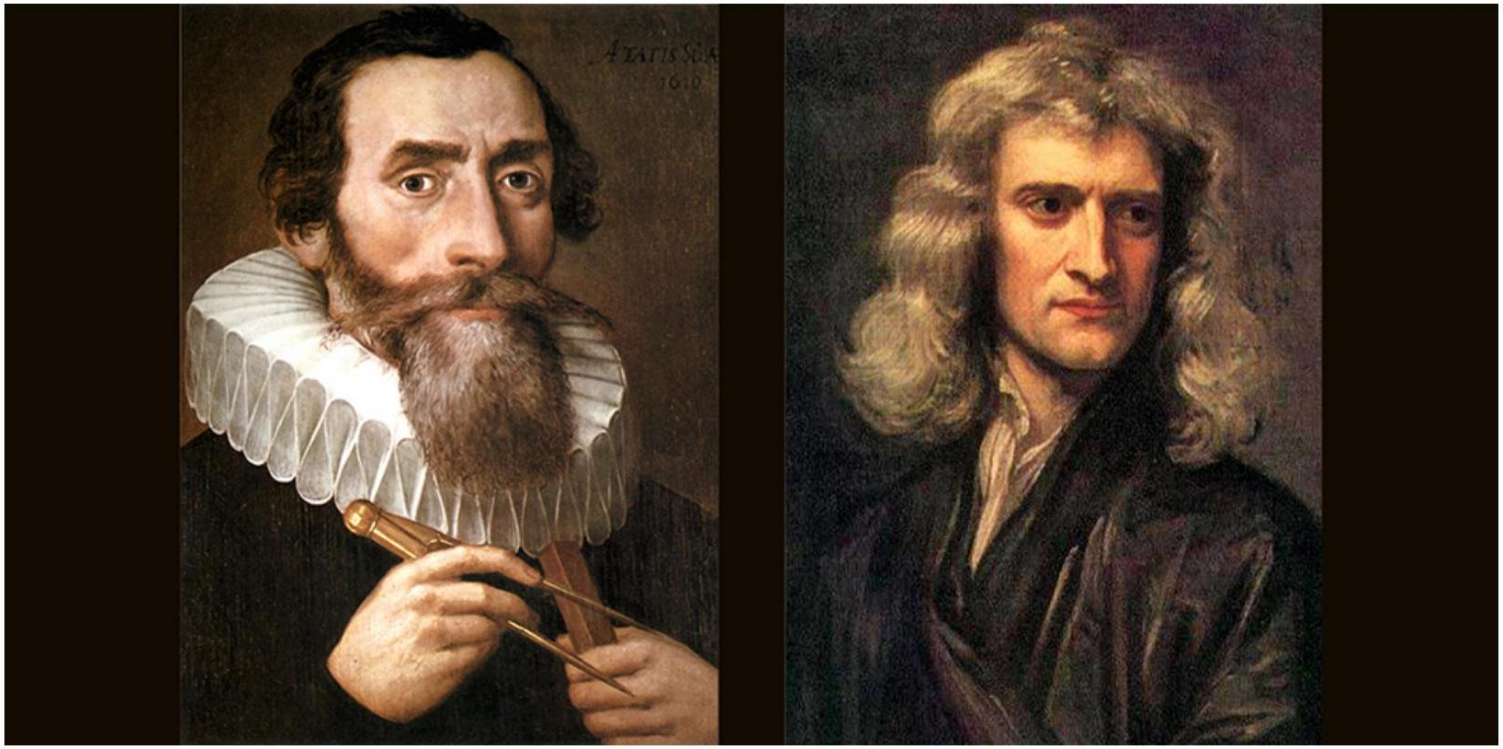


Figure: Kepler found patterns. Newton found cause.

Learning Objectives

By the end of this section, you will be able to:

- **7.1:** Explain Kepler's three laws of planetary motion

Learning Objectives

By the end of this section, you will be able to:

- **7.1:** Explain Kepler's three laws of planetary motion
- **7.1:** Apply Kepler's laws to calculate characteristics of orbits

7.1 The Rules of Orbits

Kepler studied planetary motion for 20 years

7.1 The Rules of Orbits

Kepler studied planetary motion for 20 years

Three laws describing all orbits:

1. Planets orbit in ellipses with sun at one focus

7.1 The Rules of Orbits

Kepler studied planetary motion for 20 years

Three laws describing all orbits:

1. Planets orbit in ellipses with sun at one focus
2. Equal areas in equal times

7.1 The Rules of Orbits

Kepler studied planetary motion for 20 years

Three laws describing all orbits:

1. Planets orbit in ellipses with sun at one focus
2. Equal areas in equal times
3. Period squared proportional to radius cubed

7.1 The Rules of Orbits

Kepler studied planetary motion for 20 years

Three laws describing all orbits:

1. Planets orbit in ellipses with sun at one focus
2. Equal areas in equal times
3. Period squared proportional to radius cubed

The Mental Model

Kepler found patterns in mountains of data. Described WHAT happens, not WHY.

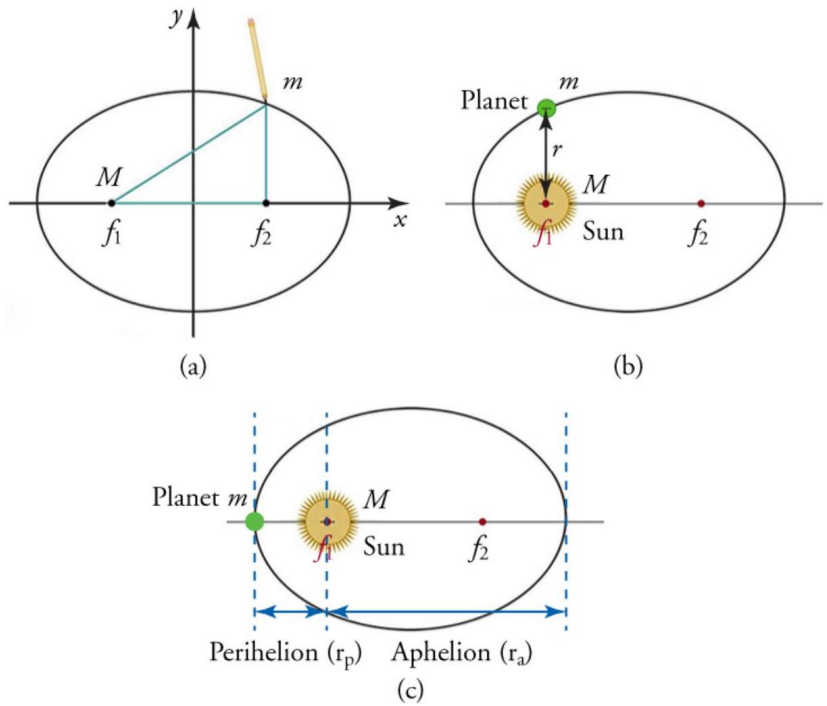
7.1 Kepler's First Law

The Law of Elliptical Orbits

Orbit of each planet is ellipse with sun at one focus.

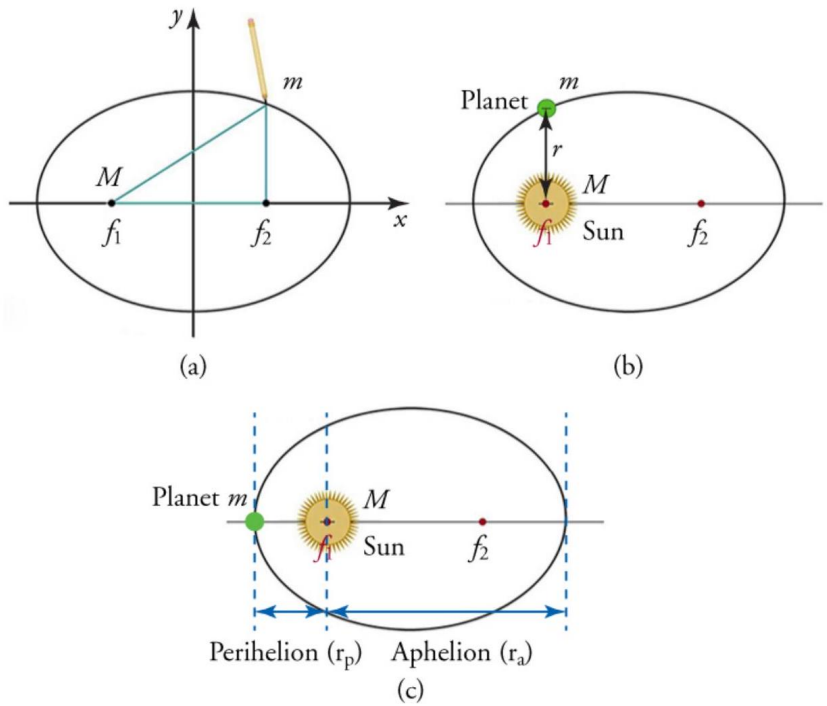
The Law of Elliptical Orbits

Orbit of each planet is ellipse with sun at one focus.



The Law of Elliptical Orbits

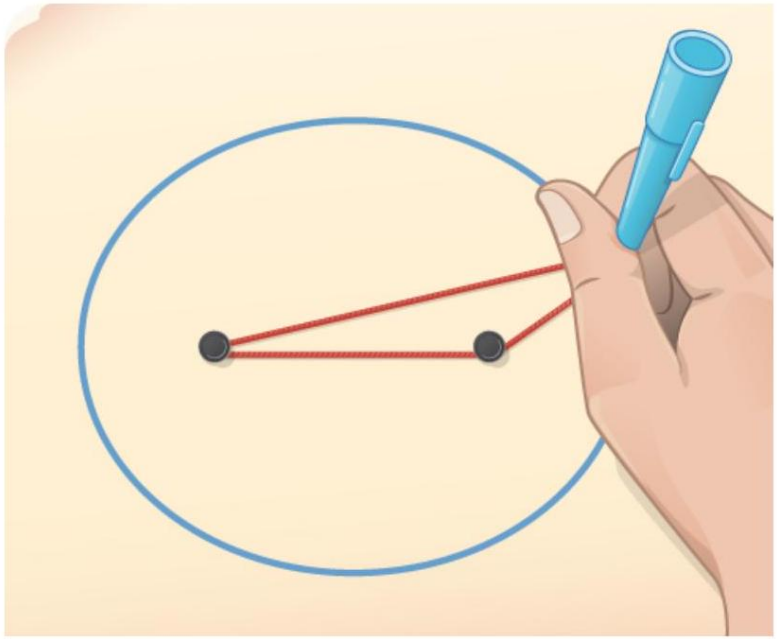
Orbit of each planet is ellipse with sun at one focus.



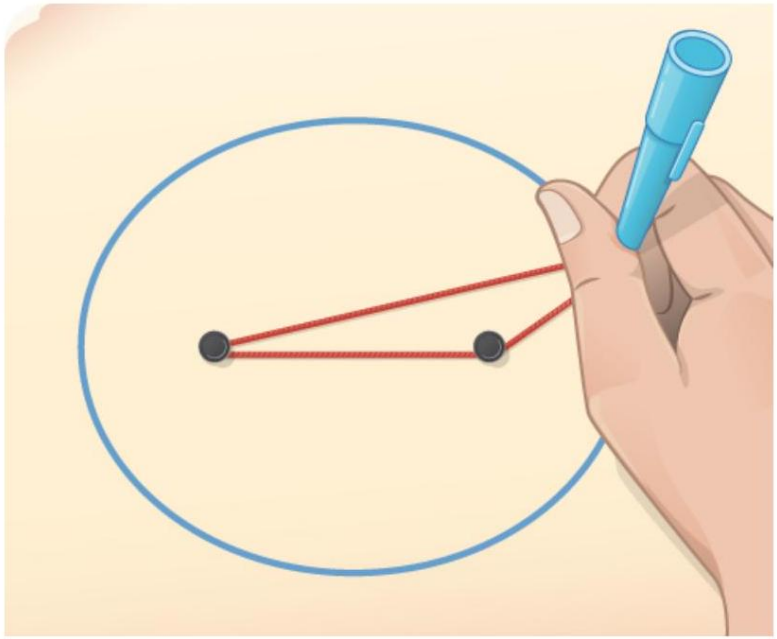
Perihelion: Closest approach to sun

Aphelion: Farthest distance from sun

7.1 Anatomy of an Ellipse

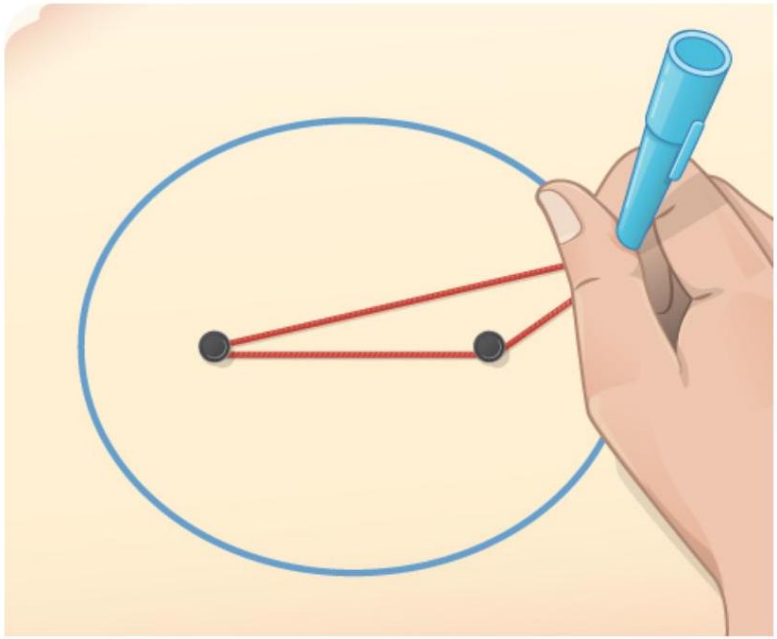


7.1 Anatomy of an Ellipse



Key property: Sum of distances from any point to both foci is constant.

7.1 Anatomy of an Ellipse



Key property: Sum of distances from any point to both foci is constant.

Drawing an ellipse: Pins, string, pencil method!

7.1 Ellipse Formulas

If you know perihelion r_p and aphelion r_a:

7.1 Ellipse Formulas

If you know perihelion r_p and aphelion r_a:

$$\text{Semi-major axis: } a = \frac{r_a + r_p}{2} \tag{1}$$

$$\text{Semi-minor axis: } b = \sqrt{r_a r_p} \tag{2}$$

7.1 Ellipse Formulas

If you know perihelion r_p and aphelion r_a:

$$\text{Semi-major axis: } a = \frac{r_a + r_p}{2} \tag{1}$$

$$\text{Semi-minor axis: } b = \sqrt{r_a r_p} \tag{2}$$

Eccentricity (elongation measure):

$$e = \frac{f}{a}$$

7.1 Ellipse Formulas

If you know perihelion r_p and aphelion r_a:

$$\text{Semi-major axis: } a = \frac{r_a + r_p}{2} \tag{1}$$

$$\text{Semi-minor axis: } b = \sqrt{r_a r_p} \tag{2}$$

Eccentricity (elongation measure):

$$e = \frac{f}{a}$$

When $e = 0$, ellipse is circle!

7.1 Kepler's Second Law

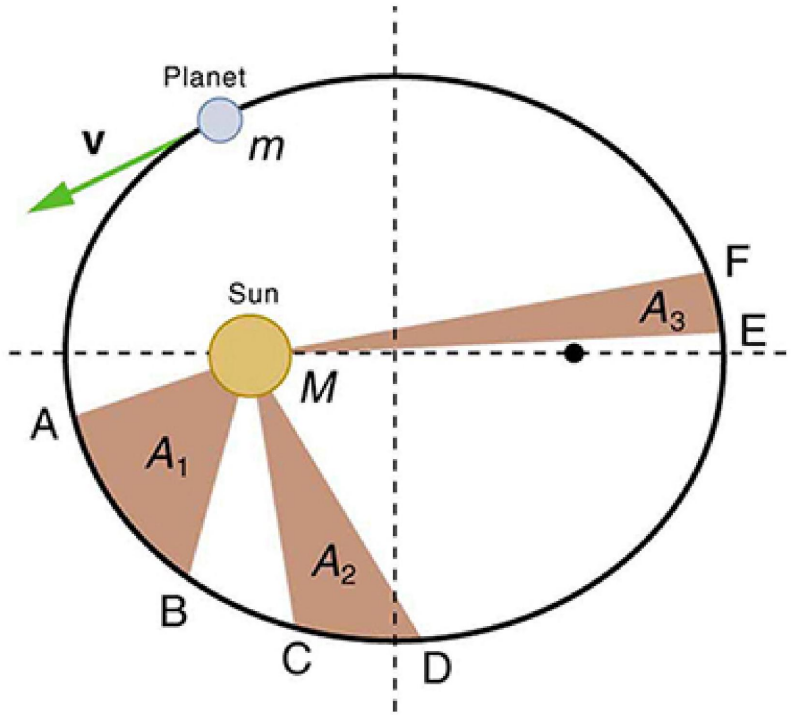
The Law of Equal Areas

Line from sun to planet sweeps equal areas in equal times.

7.1 Kepler's Second Law

The Law of Equal Areas

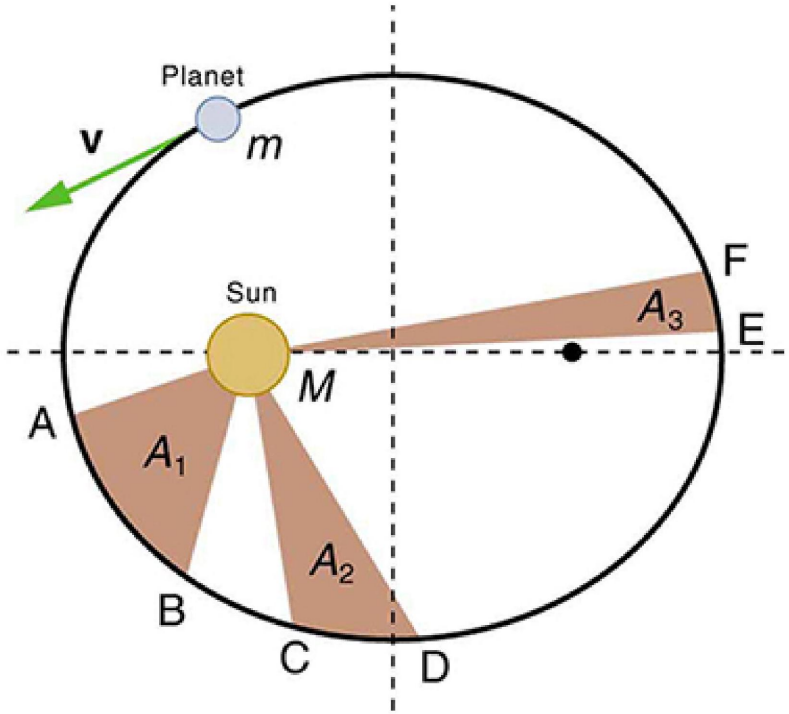
Line from sun to planet sweeps equal areas in equal times.



7.1 Kepler's Second Law

The Law of Equal Areas

Line from sun to planet sweeps equal areas in equal times.



The Paradox

Result: Planets move FASTER when closer to sun!

7.1 Kepler's Third Law

The Law of Periods

Ratio of periods squared equals ratio of orbital radii cubed.

7.1 Kepler's Third Law

The Law of Periods

Ratio of periods squared equals ratio of orbital radii cubed.

$$\boxed{\frac{T_1^2}{T_2^2} = \frac{r_1^3}{r_2^3}}$$

7.1 Kepler's Third Law

The Law of Periods

Ratio of periods squared equals ratio of orbital radii cubed.

$$\boxed{\frac{T_1^2}{T_2^2} = \frac{r_1^3}{r_2^3}}$$

Where:

- T = period (time for one orbit)
- r = average orbital radius

7.1 Kepler's Third Law

The Law of Periods

Ratio of periods squared equals ratio of orbital radii cubed.

$$\boxed{\frac{T_1^2}{T_2^2} = \frac{r_1^3}{r_2^3}}$$

Where:

- T = period (time for one orbit)
- r = average orbital radius

Critical: Only works for satellites orbiting SAME parent body!

7.1 Ptolemy vs Copernicus

Ptolemaic (Geocentric)

- Earth at center
- Complex circular paths
- Different rule each planet
- Purely descriptive

7.1 Ptolemy vs Copernicus

Ptolemaic (Geocentric)

- Earth at center
- Complex circular paths
- Different rule each planet
- Purely descriptive

Copernican (Heliocentric)

- Sun at center
- Simple elliptical paths
- Same laws for all
- Causal explanation

7.1 Ptolemy vs Copernicus

Ptolemaic (Geocentric)

- Earth at center
- Complex circular paths
- Different rule each planet
- Purely descriptive

Copernican (Heliocentric)

- Sun at center
- Simple elliptical paths
- Same laws for all
- Causal explanation

The Conflict

For 1400 years, everyone believed Earth center. Copernicus terrified to publish.

Attempt: Moon and Satellite Orbits

The Challenge (3 min, silent)

Moon orbits Earth every 27.3 days at average distance 3.84×10^8 m from Earth's center.

Given:

- Moon: $T_1 = 27.3$ d, $r_1 = 3.84 \times 10^8$ m
- Satellite: altitude $= 1500$ km above surface
- Earth radius $= 6380$ km

Find: Period of satellite

Can you predict how long this orbit takes? Work silently.

Compare: Orbital Calculations

Turn and talk (2 min):

1. What is r_2 for satellite? Did you add Earth's radius?
2. Which version Kepler's third law use?
3. Did you solve for T_2 correctly?

Compare: Orbital Calculations

Turn and talk (2 min):

1. What is r_2 for satellite? Did you add Earth's radius?
2. Which version Kepler's third law use?
3. Did you solve for T_2 correctly?

Name wheel: One pair share approach (not answer).

Reveal: Satellite Period

Self-correct in different color:

Step 1: Find orbital radius: $r_2 = 1500 \text{ km} + 6380 \text{ km} = 7880 \text{ km}$

Reveal: Satellite Period

Self-correct in different color:

Step 1: Find orbital radius: $r_2 = 1500\ \text{km} + 6380\ \text{km} = 7880\ \text{km}$

Step 2: Use Kepler's third law: $T_2 = T_1 \left(\frac{r_2}{r_1}\right)^{3/2}$

Reveal: Satellite Period

Self-correct in different color:

Step 1: Find orbital radius: $r_2 = 1500\ \text{km} + 6380\ \text{km} = 7880\ \text{km}$

Step 2: Use Kepler's third law: $T_2 = T_1 \left(\frac{r_2}{r_1}\right)^{3/2}$

Step 3: Substitute and solve:

$$T_2 = (27.3\ \text{d}) \left(\frac{24.0\ \text{h}}{\text{d}}\right) \left(\frac{7880\ \text{km}}{3.84 \times 10^5\ \text{km}}\right)^{3/2}$$

Reveal: Satellite Period

Self-correct in different color:

Step 1: Find orbital radius: $r_2 = 1500\ \text{km} + 6380\ \text{km} = 7880\ \text{km}$

Step 2: Use Kepler's third law: $T_2 = T_1 \left(\frac{r_2}{r_1}\right)^{3/2}$

Step 3: Substitute and solve:

$$T_2 = (27.3\ \text{d}) \left(\frac{24.0\ \text{h}}{\text{d}}\right) \left(\frac{7880\ \text{km}}{3.84 \times 10^5\ \text{km}}\right)^{3/2}$$

$$\boxed{T_2 = 1.93\ \text{h}}$$

Reveal: Satellite Period

Self-correct in different color:

Step 1: Find orbital radius: $r_2 = 1500\ \text{km} + 6380\ \text{km} = 7880\ \text{km}$

Step 2: Use Kepler's third law: $T_2 = T_1 \left(\frac{r_2}{r_1}\right)^{3/2}$

Step 3: Substitute and solve:

$$T_2 = (27.3\ \text{d}) \left(\frac{24.0\ \text{h}}{\text{d}}\right) \left(\frac{7880\ \text{km}}{3.84 \times 10^5\ \text{km}}\right)^{3/2}$$

$$\boxed{T_2 = 1.93\ \text{h}}$$

Check: Closer orbit = shorter period. Makes sense!

Learning Objectives

By the end of this section, you will be able to:

- **7.2:** Explain Newton's law of universal gravitation

Learning Objectives

By the end of this section, you will be able to:

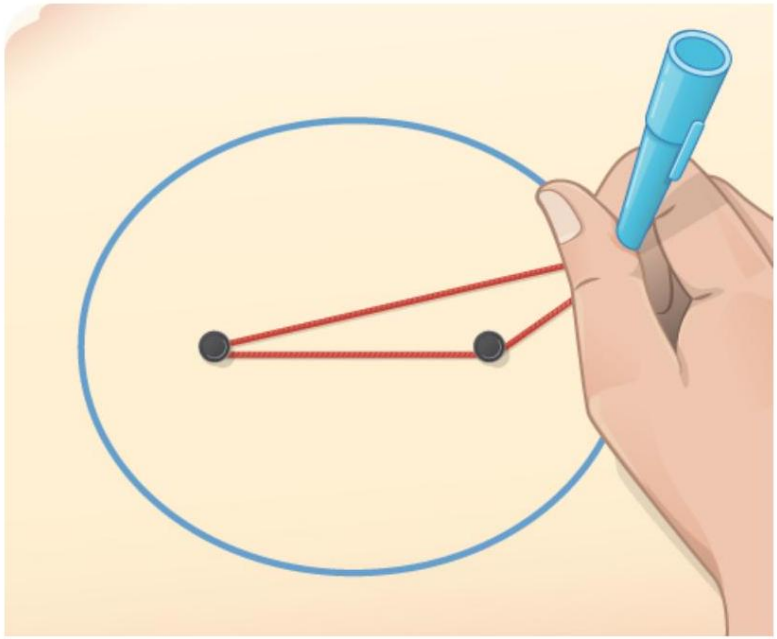
- **7.2:** Explain Newton's law of universal gravitation
- **7.2:** Perform calculations using Newton's law

Learning Objectives

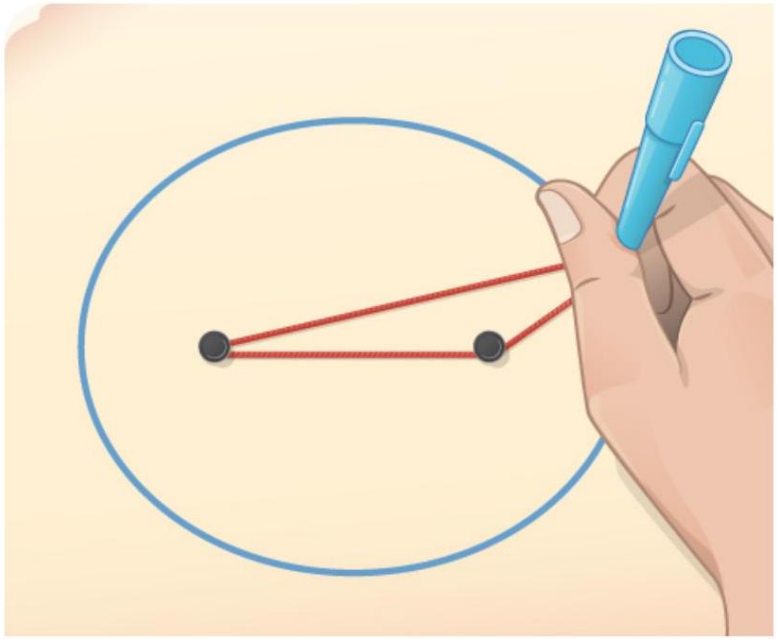
By the end of this section, you will be able to:

- **7.2:** Explain Newton's law of universal gravitation
- **7.2:** Perform calculations using Newton's law
- **7.2:** Compare Newton's theory to Einstein's general relativity

7.2 The Apple and Moon



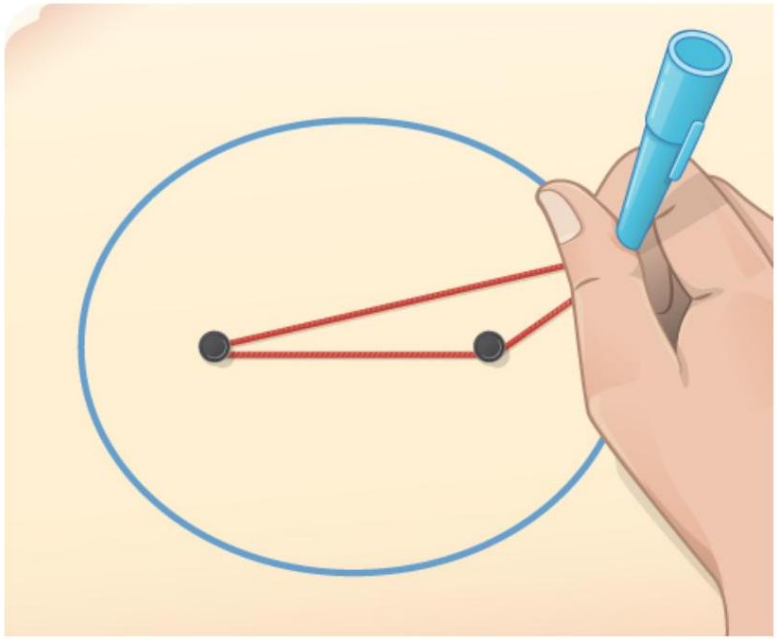
7.2 The Apple and Moon



Newton's Insight

Why do apples fall straight down? What if same force pulling apples also pulls moon?

7.2 The Apple and Moon



Newton's Insight

Why do apples fall straight down? What if same force pulling apples also pulls moon?

Revolutionary idea: Terrestrial and celestial motion have SAME cause!

7.2 Newton's Law of Universal Gravitation

The Universal Law

$$\boxed{F = G\frac{mM}{r^2}}$$

Every mass attracts every other mass with force proportional to product of masses and inversely proportional to distance squared.

7.2 Newton's Law of Universal Gravitation

The Universal Law

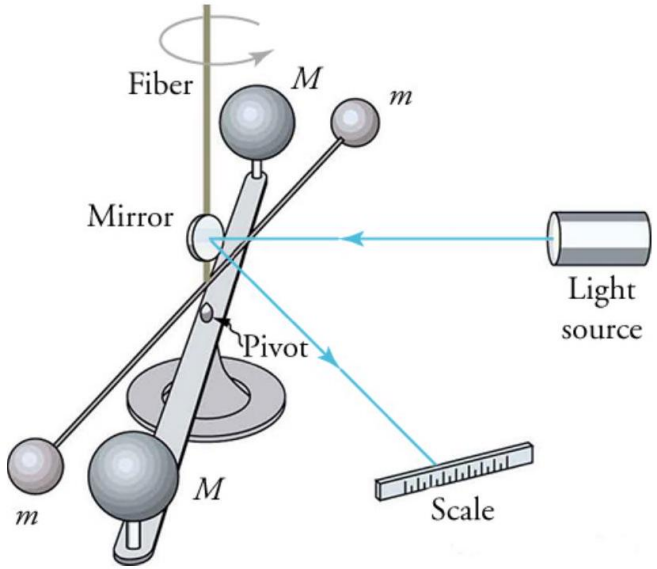
$$\boxed{F = G\frac{mM}{r^2}}$$

Every mass attracts every other mass with force proportional to product of masses and inversely proportional to distance squared.

Where:

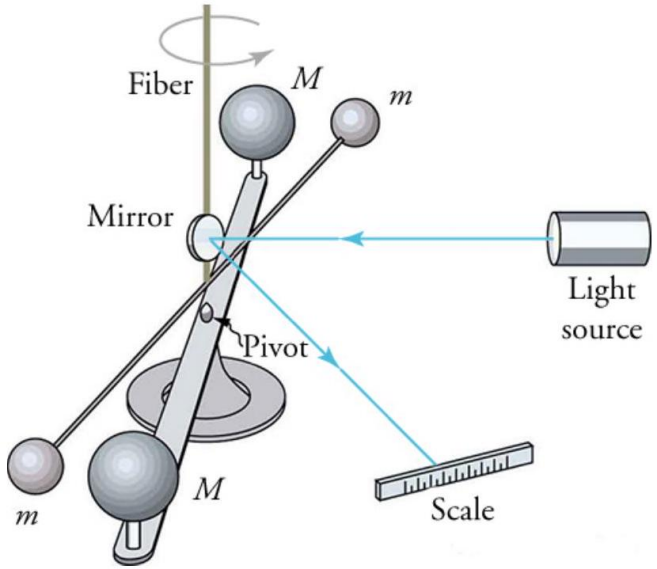
- F = gravitational force (N)
- $G = 6.67 \times 10^{-11}$ N·m²/kg² (universal constant)
- m, M = masses (kg)
- r = distance between centers (m)

7.2 The Gravitational Constant



Cavendish's torsion balance (1798)

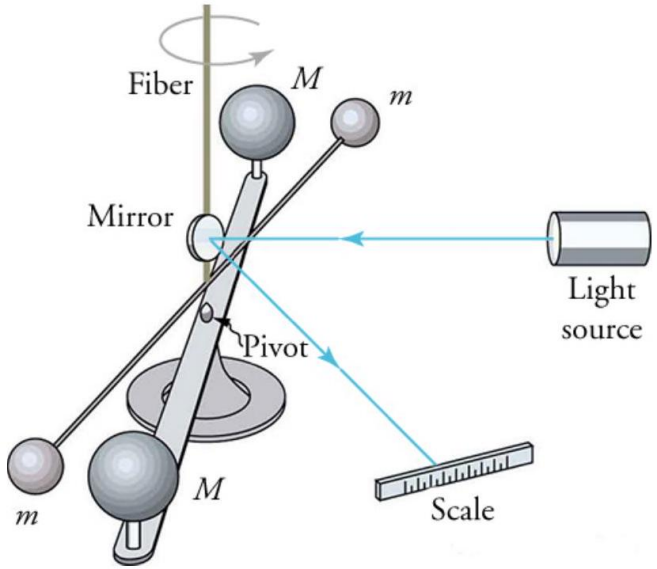
7.2 The Gravitational Constant



Cavendish's torsion balance (1798)

Challenge: Measuring tiny force between ordinary masses

7.2 The Gravitational Constant

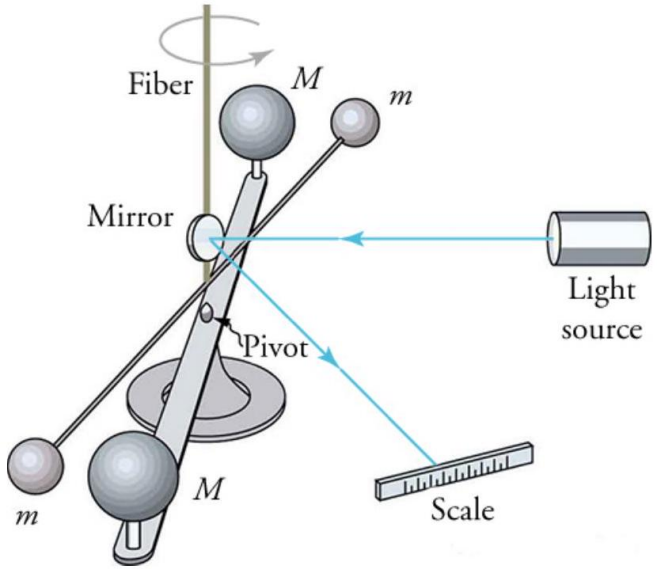


Cavendish's torsion balance (1798)

Challenge: Measuring tiny force between ordinary masses

Result: $G = 6.67 \times 10^{-11}$ N·m²/kg²

7.2 The Gravitational Constant



Cavendish's torsion balance (1798)

Challenge: Measuring tiny force between ordinary masses

Result: $G = 6.67 \times 10^{-11}$ N·m²/kg²
Cavendish's value differs less than 1% from modern value!

7.2 Mass vs Weight

Civilian View vs Reality

Civilian: "Mass and weight same thing."
Physicist: "Mass constant. Weight varies with gravity."

7.2 Mass vs Weight

Civilian View vs Reality

Civilian: "Mass and weight same thing."
Physicist: "Mass constant. Weight varies with gravity."

Mass: Amount of matter (kg) - constant everywhere

7.2 Mass vs Weight

Civilian View vs Reality

Civilian: "Mass and weight same thing."
Physicist: "Mass constant. Weight varies with gravity."

Mass: Amount of matter (kg) - constant everywhere
Weight: Gravitational force (N) - varies by location

$$W = mg$$

7.2 Mass vs Weight

Civilian View vs Reality

Civilian: "Mass and weight same thing."
Physicist: "Mass constant. Weight varies with gravity."

Mass: Amount of matter (kg) - constant everywhere
Weight: Gravitational force (N) - varies by location

$$W = mg$$

Your mass on moon same as Earth. Your weight 1/6 as much!

7.2 Connecting to Kepler

Newton derived Kepler's third law from universal gravitation!

7.2 Connecting to Kepler

Newton derived Kepler's third law from universal gravitation!

Result:

$$\frac{r^3}{T^2} = \frac{GM}{4\pi^2}$$

7.2 Connecting to Kepler

Newton derived Kepler's third law from universal gravitation!

Result:

$$\frac{r^3}{T^2} = \frac{GM}{4\pi^2}$$

The Revelation

Kepler said WHAT (pattern). Newton said WHY (gravitational force causes it).

7.2 Connecting to Kepler

Newton derived Kepler's third law from universal gravitation!

Result:

$$\frac{r^3}{T^2} = \frac{GM}{4\pi^2}$$

The Revelation

Kepler said WHAT (pattern). Newton said WHY (gravitational force causes it).

Power: If you know r and T, can calculate mass M of parent body!

Attempt: Weight on Mars

The Challenge (3 min, silent)

Value of g on Mars is 3.71 m/s². You have mass 60.0 kg on Earth.

Given:

- Your mass: $m = 60.0$ kg
- Mars gravity: $g_M = 3.71$ m/s²
- Earth gravity: $g_E = 9.80$ m/s²

Find:

1. What is your mass on Mars?
2. What is your weight on Mars?

How much would you weigh on Mars? Work silently.

Compare: Mass and Weight

Turn and talk (2 min):

1. Does mass change when go Mars? Why or why not?
2. What formula use for weight on Mars?
3. How Mars weight compare Earth weight?

Compare: Mass and Weight

Turn and talk (2 min):

1. Does mass change when go Mars? Why or why not?
2. What formula use for weight on Mars?
3. How Mars weight compare Earth weight?

Name wheel: One pair share reasoning.

Reveal: Mars Weight

Self-correct in different color:

Part 1: Mass on Mars = **60.0 kg** (mass constant!)

Reveal: Mars Weight

Self-correct in different color:

Part 1: Mass on Mars $=$ **60.0 kg** (mass constant!)

Part 2: Weight on Mars: $W_M = mg_M$

Reveal: Mars Weight

Self-correct in different color:

Part 1: Mass on Mars = **60.0 kg** (mass constant!)

Part 2: Weight on Mars: $W_M = mg_M$

$$W_M = (60.0 \text{ kg})(3.71 \text{ m/s}^2)$$

Reveal: Mars Weight

Self-correct in different color:

Part 1: Mass on Mars = **60.0 kg** (mass constant!)

Part 2: Weight on Mars: $W_M = mg_M$

$$W_M = (60.0 \text{ kg})(3.71 \text{ m/s}^2)$$

$$\boxed{W_M = 223 \text{ N}}$$

Reveal: Mars Weight

Self-correct in different color:

Part 1: Mass on Mars = **60.0 kg** (mass constant!)

Part 2: Weight on Mars: $W_M = mg_M$

$$W_M = (60.0 \text{ kg})(3.71 \text{ m/s}^2)$$

$$\boxed{W_M = 223 \text{ N}}$$

Compare: Earth weight $= (60.0)(9.80) = 588$ N

Reveal: Mars Weight

Self-correct in different color:

Part 1: Mass on Mars = **60.0 kg** (mass constant!)

Part 2: Weight on Mars: $W_M = mg_M$

$$W_M = (60.0 \text{ kg})(3.71 \text{ m/s}^2)$$

$$\boxed{W_M = 223 \text{ N}}$$

Compare: Earth weight $= (60.0)(9.80) = 588$ N
Mars weight about 38% Earth weight!

7.2 Einstein's General Relativity

Newton's theory works perfectly most situations...

7.2 Einstein's General Relativity

Newton's theory works perfectly most situations...

But Einstein showed gravity more than just force:

7.2 Einstein's General Relativity

Newton's theory works perfectly most situations...

But Einstein showed gravity more than just force:

- Gravity warps space and time

7.2 Einstein's General Relativity

Newton's theory works perfectly most situations...

But Einstein showed gravity more than just force:

- Gravity warps space and time
- Light bends in gravitational fields

7.2 Einstein's General Relativity

Newton's theory works perfectly most situations...

But Einstein showed gravity more than just force:

- Gravity warps space and time
- Light bends in gravitational fields
- Massive objects drag space-time with them

7.2 Einstein's General Relativity

Newton's theory works perfectly most situations...

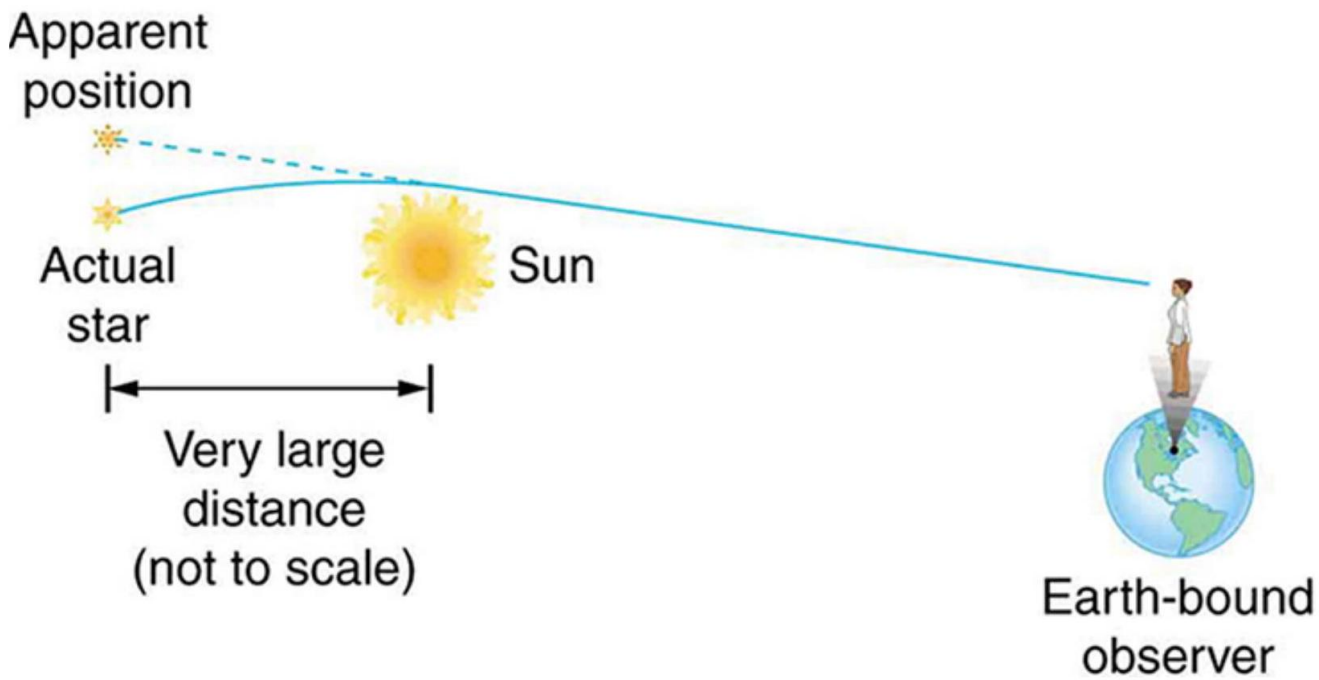
But Einstein showed gravity more than just force:

- Gravity warps space and time
- Light bends in gravitational fields
- Massive objects drag space-time with them

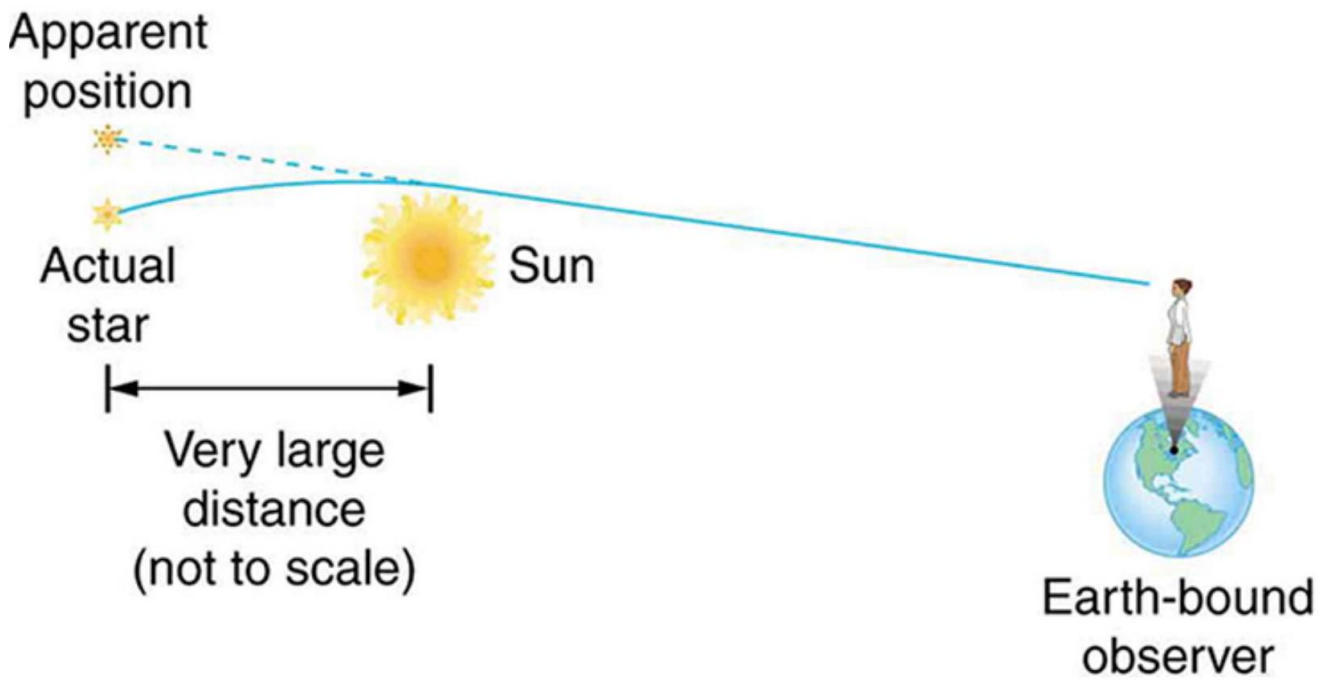
The Mental Model

Newton: Gravity tug of war between masses.
Einstein: Gravity bending of space-time itself.

7.2 Light Bending Around Sun

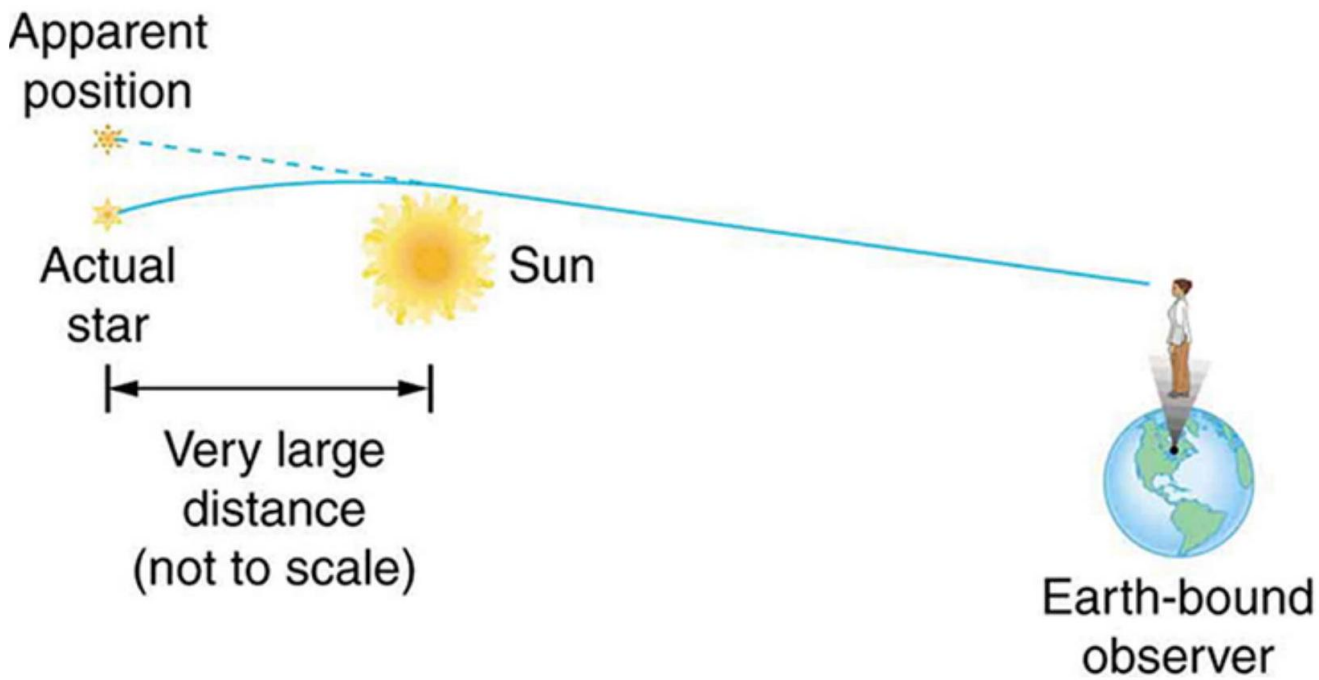


7.2 Light Bending Around Sun



1919 solar eclipse: Starlight bent exactly as Einstein predicted!

7.2 Light Bending Around Sun



1919 solar eclipse: Starlight bent exactly as Einstein predicted!
Made Einstein scientific celebrity overnight.

Attempt: Earth's Gravity at Moon Distance

The Challenge (3 min, silent)

Find acceleration due Earth's gravity at moon's distance.

Given:

- $G = 6.67 \times 10^{-11}$ N·m²/kg²
- Earth mass: $M = 5.98 \times 10^{24}$ kg
- Earth-moon distance: $r = 3.84 \times 10^{8}$ m

Find: Value g at moon's distance from Earth

How weak is Earth's pull at that distance? Work silently.

Compare: Gravity Calculation

Turn and talk (2 min):

1. What formula use for g?
2. How handle scientific notation?
3. How this g compare Earth's surface $g = 9.8$ m/s^2?

Compare: Gravity Calculation

Turn and talk (2 min):

1. What formula use for g?
2. How handle scientific notation?
3. How this g compare Earth's surface $g = 9.8$ m/s^2?

Name wheel: One pair share approach.

Reveal: Gravity at Moon Distance

Self-correct in different color:

Formula: $g = G\frac{M}{r^2}$

Reveal: Gravity at Moon Distance

Self-correct in different color:

Formula: $g = G\frac{M}{r^2}$

Substitute:

$$g = \left(6.67 \times 10^{-11}\,\frac{\text{N}\cdot\text{m}^2}{\text{kg}^2}\right)\left(\frac{5.98 \times 10^{24}\ \text{kg}}{(3.84 \times 10^{8}\ \text{m})^2}\right)$$

Reveal: Gravity at Moon Distance

Self-correct in different color:

Formula: $g = G\frac{M}{r^2}$

Substitute:

$$g = \left(6.67 \times 10^{-11}\,\frac{\text{N}\cdot\text{m}^2}{\text{kg}^2}\right)\left(\frac{5.98 \times 10^{24}\ \text{kg}}{(3.84 \times 10^{8}\ \text{m})^2}\right)$$

$$g = \frac{3.99 \times 10^{14}}{1.47 \times 10^{17}}$$

Reveal: Gravity at Moon Distance

Self-correct in different color:

Formula: $g = G\frac{M}{r^2}$

Substitute:

$$g = \left(6.67 \times 10^{-11}\,\frac{\text{N}\cdot\text{m}^2}{\text{kg}^2}\right)\left(\frac{5.98 \times 10^{24}\ \text{kg}}{(3.84 \times 10^{8}\ \text{m})^2}\right)$$

$$g = \frac{3.99 \times 10^{14}}{1.47 \times 10^{17}}$$

$$\boxed{g = 2.70 \times 10^{-3}\ \text{m/s}^2}$$

Reveal: Gravity at Moon Distance

Self-correct in different color:

Formula: $g = G\frac{M}{r^2}$

Substitute:

$$g = \left(6.67 \times 10^{-11}\,\frac{\text{N}\cdot\text{m}^2}{\text{kg}^2}\right)\left(\frac{5.98 \times 10^{24}\ \text{kg}}{(3.84 \times 10^{8}\ \text{m})^2}\right)$$

$$g = \frac{3.99 \times 10^{14}}{1.47 \times 10^{17}}$$

$$\boxed{g = 2.70 \times 10^{-3}\ \text{m/s}^2}$$

Compare: About 0.03% Earth's surface gravity!

What You Now Know

The Revelations

1. Kepler found three laws describing orbital motion

What You Now Know

The Revelations

1. Kepler found three laws describing orbital motion
2. Newton discovered gravitational force explains Kepler's laws

What You Now Know

The Revelations

1. Kepler found three laws describing orbital motion
2. Newton discovered gravitational force explains Kepler's laws
3. Universal gravitation: $F = Gm_1m_2/r^2$

What You Now Know

The Revelations

1. Kepler found three laws describing orbital motion
2. Newton discovered gravitational force explains Kepler's laws
3. Universal gravitation: $F = Gm_1m_2/r^2$
4. Mass constant, weight varies with g

What You Now Know

The Revelations

1. Kepler found three laws describing orbital motion
2. Newton discovered gravitational force explains Kepler's laws
3. Universal gravitation: $F = Gm_1m_2/r^2$
4. Mass constant, weight varies with g
5. Einstein showed gravity warps space-time itself

What You Now Know

The Revelations

1. Kepler found three laws describing orbital motion
2. Newton discovered gravitational force explains Kepler's laws
3. Universal gravitation: $F = Gm_1m_2/r^2$
4. Mass constant, weight varies with g
5. Einstein showed gravity warps space-time itself
6. Same force governs falling apples and orbiting galaxies

Key Equations

$$\text{Kepler's Third Law: } \frac{T_1^2}{T_2^2} = \frac{r_1^3}{r_2^3} \tag{3}$$

$$\text{Universal Gravitation: } F = G\frac{mM}{r^2} \tag{4}$$

$$\text{Gravitational Constant: } G = 6.67 \times 10^{-11}\ \text{N}\cdot\text{m}^2/\text{kg}^2 \tag{5}$$

$$\text{Weight: } W = mg \tag{6}$$

$$\text{Surface Gravity: } g = G\frac{M}{r^2} \tag{7}$$

$$\text{Orbital Constant: } \frac{r^3}{T^2} = \frac{GM}{4\pi^2} \tag{8}$$

Homework

Complete assigned problems

posted on LMS

Temporary page!

LaTeX was unable to guess the total number of pages correctly. A
was some unprocessed data that should have been added to the
this extra page has been added to receive it.
If you rerun the document (without altering it) this surplus page
away, because LaTeX now knows how many pages to expect for t
document.