In The Beginning
and
Cosmology Becomes a Science
Naked-eye (unaïded-eye) astronomy had an important place in ancient civilizations

• **Positional astronomy**
  – the study of the positions of objects in the sky and how these positions change
  – importance in navigation

• **Naked-eye (unaïded-eye) astronomy**
  – the sort that requires no equipment but human vision

• **Extends far back in time, across all cultures**
  – British Isles Stonehenge
  – Native American Medicine Wheel
  – Aztec, Mayan and Incan temples
  – Egyptian pyramids
Astronomical observations led to the development of the modern calendar

• The day
  – based on the Earth’s rotation
• The year
  – based on the Earth’s orbit
• The month
  – based on the lunar cycle
• None of these are exactly the same as nature so astronomers use the average or mean day and leap years to keep the calendar and time consistent
Astronomers use angles to denote the positions and apparent sizes of objects in the sky.

- The basic unit of angular measure is the **degree** (°).
- Astronomers use angular measure to describe the apparent size of a celestial object—what fraction of the sky that object seems to cover.
- The **angular diameter** (or **angular size**) of the Moon is ½° or the Moon **subtends** an angle of ½°.
If you draw lines from your eye to each of two stars, the angle between these lines is the **angular distance** between these two stars.
The adult human hand held at arm’s length provides a means of estimating angles.
Angular Measurements

• Subdivide one degree into 60 arcminutes
  – minutes of arc
  – abbreviated as 60 arcmin or 60´

• Subdivide one arcminute into 60 arcseconds
  – seconds of arc
  – abbreviated as 60 arcsec or 60”

1° = 60 arcmin = 60´
1´ = 60 arcsec = 60”
Powers-of-ten notation – a useful shorthand system for writing numbers
### Common Prefixes for Powers of Ten

<table>
<thead>
<tr>
<th>Factor</th>
<th>Name</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>(billion)</td>
<td>Giga-</td>
<td>G</td>
</tr>
<tr>
<td>(million)</td>
<td>Mega-</td>
<td>M</td>
</tr>
<tr>
<td>(thousand)</td>
<td>kilo-</td>
<td>k</td>
</tr>
<tr>
<td>(hundredth)</td>
<td>centi-</td>
<td>c</td>
</tr>
<tr>
<td>(thousandth)</td>
<td>milli-</td>
<td>m</td>
</tr>
<tr>
<td>(millionth)</td>
<td>micro-</td>
<td>μ</td>
</tr>
<tr>
<td>(billionth)</td>
<td>nano-</td>
<td>n</td>
</tr>
</tbody>
</table>
Astronomical distances are often measured in astronomical units, parsecs, or light-years

- **Astronomical Unit (AU)**
  - One AU is the average distance between Earth and the Sun
  - $1.496 \times 10^8$ km or 92.96 million miles

- **Light Year (ly)**
  - One ly is the distance light can travel in one year at a speed of about $3 \times 10^5$ km/s or 186,000 miles/s
  - $9.46 \times 10^{12}$ km or 63,240 AU

- **Parsec (pc)**
  - the distance at which 1 AU subtends an angle of 1 arcsec or the distance from which Earth would appear to be one arcsecond from the Sun
  - $1 \text{ pc} = 3.09 \times 10^{13}$ km = 3.26 ly
In January, the nearby star appears to be here.

In July, the nearby star appears to be here.

Parallax of a nearby star
The closer the star, the more its apparent position shifts as seen from Earth.

Parallax of an even closer star
The parallax of stars reveals their distances

Relation between a star’s distance and its parallax

\[ d = \frac{1}{p} \]

- Distance to a star, in parsecs
- Parallax angle of that star, in arcseconds

- Distances to the nearer stars can be determined by parallax, the apparent shift of a star against the background stars observed as the Earth moves along its orbit.
- Parallax measurements made from orbit, above the blurring effects of the atmosphere, are much more accurate than those made with Earth-based telescopes.
- Stellar parallaxes can only be measured for stars within a few hundred parsecs.
Barnard’s star has a parallax of 0.54 arcsec

\[ d = \frac{1}{p} = \frac{1}{0.547} = 1.83 \text{ pc} \]

Because 1 parsec is 3.26 light-years, this can also be expressed as

\[ d = 1.83 \text{ pc} \times \frac{3.26 \text{ ly}}{1 \text{ pc}} = 5.96 \text{ ly} \]
At a distance of 1 parsec, a length of 1 AU subtends an angle of 1 arcsec.
The Small Angle Formula

\[ D = \frac{\alpha d}{206265} \]

- \( D \) = linear size of object
- \( \alpha \) = angular size of object (in arcsec)
- \( d \) = distance to the object
Small Angle Formula Example

- On July 26, 2003, Jupiter was 943 million kilometers from Earth and had an angular diameter of 31.2”.
- Using the small-angle formula, determine Jupiter’s actual diameter.

\[
D = \frac{31.2'' \times 943 \times 10^6 \text{ km}}{206265} = 1.43 \times 10^5 \text{ km}
\]
The Sun and full Moon have about the same angular size on the sky of 0.5 degrees. Why?
A. the sun and moon are the same size and the same distance from Earth, but always in different parts of the sky.
B. the moon is bigger than the sun and farther from Earth
C. all spherical objects have the same angular size on the sky
D. the moon is smaller than the sun, but closer to Earth
E. none of the above
Eighty-eight constellations officially cover the entire sky

- Ancient peoples looked at the stars and imagined groupings
  - Pictures in the sky
  - Different cultures different pictures
- We still refer to many of these groupings
- Astronomers call them constellations (from the Latin for “group of stars”)
  - Parts are asterisms

Eighty-eight constellations officially cover the entire sky.
Modern Constellations

• On modern star charts, the entire sky is divided into 88 regions
  – Each is a constellation
• Most stars in a constellation are nowhere near one another
• They only appear to be close together because they are in nearly the same direction as seen from Earth
  – Need to think in three dimensions
The appearance of the sky changes during the course of the night and from one night to the next.

- Stars appear to rise in the east, slowly rotate about the Earth and set in the west.
- This diurnal or daily motion of the stars is actually caused by the 24-hour rotation of the Earth.
Annual Motion

- The stars also appear to slowly shift in position throughout the year.
- This is due to the orbit of the earth around the sun.
- If you follow a particular star on successive evenings, you will find that it rises approximately 4 minutes earlier each night, or 2 hours earlier each month.
It was common to imagine that the stars are located on a celestial sphere.

- The celestial sphere is an *imaginary* object that has no basis in physical reality.
- However, it is still a model that remains a useful tool of positional astronomy.
- Landmarks on the celestial sphere are projections of those on the Earth.
• Celestial equator divides the sky into northern and southern hemispheres.

• Celestial poles are where the Earth’s axis of rotation would intersect the celestial sphere.

• Polaris is less than 1° away from the north celestial pole, which is why it is called the North Star or the Pole Star.

• Point in the sky directly overhead an observer anywhere on Earth is called that observer’s zenith.
  - Nadir is directly opposite the zenith.
The Reason for the Seasons

- Spring in the northern hemisphere; autumn in the southern hemisphere
- Winter in the northern hemisphere; summer in the southern hemisphere
- Summer in the northern hemisphere; winter in the southern hemisphere
- Autumn in the northern hemisphere; spring in the southern hemisphere
The seasons are caused by the tilt of Earth’s axis of rotation

- The Earth’s axis of rotation is not perpendicular to the plane of the Earth’s orbit
- It is tilted about 23½° away from the perpendicular
- The Earth maintains this tilt as it orbits the Sun, with the Earth’s north pole pointing toward the north celestial pole
(a) The Sun in summer

The Sun is high in the midday summer sky...

... so a shaft of sunlight is concentrated onto a small area, which heats the ground effectively and makes the days warm.

(b) The Sun in winter

The Sun is low in the midday winter sky...

... so the same shaft of sunlight is spread out over a larger area and less heating of the ground takes place.
The Sun appears to trace out a circular path called the **ecliptic** on the celestial sphere tilted at 23 ½ degrees to the equator.

The ecliptic and the celestial equator intersect at only two points.

Each point is called an **equinox**.

The point on the ecliptic farthest north of the celestial equator that marks the location of the Sun at the beginning of summer in the northern hemisphere is called the **summer solstice**.

At the beginning of the northern hemisphere’s winter the Sun is farthest south of the celestial equator at a point called the **winter solstice**.
The Moon helps to cause precession, a slow, conical motion of Earth’s axis of rotation.
Precession causes the gradual change of the star that marks the North Celestial Pole.
Local solar noon on March 21 is at this location on Earth.

Earth moves about 1° around its orbit in one day...

...so Earth must make a complete rotation plus 1° to bring this location to local solar noon on March 22.
The Moon’s rotation always keeps the same face toward the Earth – this is synchronous rotation.

If the Moon did not rotate, we could see all sides of the Moon.

In fact the Moon does rotate, and we see only one face of the Moon.
Ancient astronomers measured the size of the Earth and attempted to determine distances to the Sun and Moon

• Observations
  – In the town of Syene, the Sun shone directly down a vertical shaft on the summer solstice
  – In Alexandria, the position of the sun changed by 7° or about one-fiftieth of a complete circle

• Conclusion
  – Around 200 B.C., the Greek astronomer Eratosthenes used 50 x the distance between Alexandria and Syene to get a circumference of the earth of about 42000 km (the actual is about 40000 kilometers)
• Aristarchus knew that the Sun, Moon, and Earth form a right triangle at first and third quarter phases.

• Using geometrical arguments, he calculated the relative lengths of the sides of these triangles, thereby obtaining the relative distances to the Sun and Moon.
<table>
<thead>
<tr>
<th></th>
<th>Ancient measure (km)</th>
<th>Modern measure (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth’s diameter</td>
<td>13,000</td>
<td>12,756</td>
</tr>
<tr>
<td>Moon’s diameter</td>
<td>4,300</td>
<td>3,476</td>
</tr>
<tr>
<td>Sun’s diameter</td>
<td>$9 \times 10^4$</td>
<td>$1.39 \times 10^6$</td>
</tr>
<tr>
<td>Earth-Moon distance</td>
<td>$4 \times 10^5$</td>
<td>$3.84 \times 10^5$</td>
</tr>
<tr>
<td>Earth-Sun distance</td>
<td>$10^7$</td>
<td>$1.50 \times 10^8$</td>
</tr>
</tbody>
</table>
To understand the universe, astronomers use the laws of physics to construct testable theories and models

- **Scientific Method**
  - A reiterative process based on observations, logic, and skepticism
- **Hypothesis**
  - A concept or idea that seems to explain a phenomenon or set of observations
- **Model**
  - A set of hypotheses that have withstood observational or experimental tests
- **Theory**
  - A set of related hypotheses can be pieced together into a self-consistent description of natural observations
- **Laws of Physics**
  - Theories that accurately describe the workings of physical reality, and have stood the test of time and been shown to have great and general validity
Ancient astronomers invented geocentric models to explain planetary motions

- Like the Sun and Moon, the planets move on the celestial sphere with respect to the background of stars
- Most of the time a planet moves eastward in direct motion, in the same direction as the Sun and the Moon, but from time to time it moves westward in retrograde motion
• Ancient astronomers believed the Earth to be at the center of the universe
• They invented a complex system of epicycles and deferents to explain the direct and retrograde motions of the planets on the celestial sphere
The Greek geocentric model

Celestial sphere rotates to the west

Stars fixed on celestial sphere
Planetary model

- Planet moves rapidly eastward along epicycle
- Epicycle moves slowly eastward along deferent

As seen from Earth, planet moves eastward (direct motion)
Planet moves rapidly westward along epicycle

Epicycle moves slowly eastward along deferent

As seen from Earth, planet moves westward (retrograde motion)
Nicolaus Copernicus devised a comprehensive heliocentric model

- Copernicus’s heliocentric (Sun-centered) theory simplified the general explanation of planetary motions
- In a heliocentric system, the Earth is one of the planets orbiting the Sun
- The sidereal period of a planet, its true orbital period, is measured with respect to the stars
Tycho Brahe’s astronomical observations provided evidence for another model of the solar system.
Parallax – apparent difference in position of object viewed from two different locations
Johannes Kepler proposed elliptical paths for the planets about the Sun

- Using data collected by Tycho Brahe, Kepler deduced three laws of planetary motion:
  - the orbits are ellipses
    - With Sun at one focus
  - Equal areas in equal times
    - a planet’s speed varies as it moves around its elliptical orbit
  - The period squared equals the semi-major axis cubed
    - the orbital period of a planet is related to the size of its orbit
Kepler’s First Law

Major axis

Focus

Focus

Semimajor axis

Semimajor axis
Kepler’s Second Law

Sun at one focus of elliptical orbit

Perihelion

Aphelion

Planet sweeps out equal areas in equal time intervals
### Kepler’s Third Law

**Equation:**

\[ P^2 = a^3 \]

- \( P \): planet’s sidereal period, in years
- \( a \): planet’s semimajor axis, in AU

#### Table 4-3: A Demonstration of Kepler’s Third Law \( (P^2 = a^3) \)

<table>
<thead>
<tr>
<th>Planet</th>
<th>Sidereal period ( P ) (years)</th>
<th>Semimajor axis ( a ) (AU)</th>
<th>( P^2 )</th>
<th>( a^3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.24</td>
<td>0.39</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Venus</td>
<td>0.61</td>
<td>0.72</td>
<td>0.37</td>
<td>0.37</td>
</tr>
<tr>
<td>Earth</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Mars</td>
<td>1.88</td>
<td>1.52</td>
<td>3.53</td>
<td>3.51</td>
</tr>
<tr>
<td>Jupiter</td>
<td>11.86</td>
<td>5.20</td>
<td>140.7</td>
<td>140.6</td>
</tr>
<tr>
<td>Saturn</td>
<td>29.46</td>
<td>9.55</td>
<td>867.9</td>
<td>871.0</td>
</tr>
<tr>
<td>Uranus</td>
<td>84.10</td>
<td>19.19</td>
<td>7,072</td>
<td>7,067</td>
</tr>
<tr>
<td>Neptune</td>
<td>164.86</td>
<td>30.07</td>
<td>27,180</td>
<td>27,190</td>
</tr>
<tr>
<td>Pluto</td>
<td>248.60</td>
<td>39.54</td>
<td>61,800</td>
<td>61,820</td>
</tr>
</tbody>
</table>

**Verification:**

- For Mercury: \( P^2 = 0.06, a^3 = 0.06 \)
- For Venus: \( P^2 = 0.37, a^3 = 0.37 \)
- For Earth: \( P^2 = 1.00, a^3 = 1.00 \)
- For Mars: \( P^2 = 3.53, a^3 = 3.51 \)
- For Jupiter: \( P^2 = 140.7, a^3 = 140.6 \)
- For Saturn: \( P^2 = 867.9, a^3 = 871.0 \)
- For Uranus: \( P^2 = 7,072, a^3 = 7,067 \)
- For Neptune: \( P^2 = 27,180, a^3 = 27,190 \)
- For Pluto: \( P^2 = 61,800, a^3 = 61,820 \)
Kepler discovered his laws of planetary motion primarily from a study of the observations of

A  Copernicus
B  Galileo Galilei
C  Ptolemy
D  Tycho Brahe
E  Melvin Laird
Galileo’s discoveries with a telescope strongly supported a heliocentric model

- Galileo’s observations reported in 1610
  - the phases of Venus*
  - the motions of the moons of Jupiter*
  - “mountains” on the Moon
  - Sunspots on the Sun

*observations supporting heliocentric model
• One of Galileo’s most important discoveries with the telescope was that Venus exhibits phases like those of the Moon.
• Galileo also noticed that the apparent size of Venus as seen through his telescope was related to the planet’s phase.
• Venus appears small at gibbous phase and largest at crescent phase.
There is a correlation between the phases of Venus and the planet's angular distance from the Sun.
Geocentric Model Issues

- To explain why Venus is never seen very far from the Sun, the Ptolemaic model had to assume that the deferents of Venus and of the Sun move together in lockstep, with the epicycle of Venus centered on a straight line between the Earth and the Sun.

- In this model, Venus was never on the opposite side of the Sun from the Earth, and so it could never have shown the gibbous phases that Galileo observed.
• In 1610 Galileo discovered four moons of Jupiter, also called the Galilean moons or satellites.

<table>
<thead>
<tr>
<th>Observations February 1610</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Jan.</td>
</tr>
<tr>
<td>3. Jan.</td>
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<td>4. Jan.</td>
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<td>5. Jan.</td>
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<td>10. Jan.</td>
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<td>11. Jan.</td>
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<tr>
<td>12. Jan.</td>
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<tr>
<td>13. Jan.</td>
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<tr>
<td>14. Jan.</td>
</tr>
</tbody>
</table>

• This is a page from his published work in 1610.
Isaac Newton formulated three laws that describe fundamental properties of physical reality

- Called Newton’s Laws of Motion, they apply to the motions of objects on Earth as well as in space
  - a body remains at rest, or moves in a straight line at a constant speed, unless acted upon by an outside force
    - the law of inertia
  - the force on an object is directly proportional to its mass and acceleration
    - \[ F = m \times a \]
  - the principle of action and reaction
    - whenever one body exerts a force on a second body, the second body exerts an equal and opposite force on the first body
Newton's Law of Universal Gravitation

\[ F = G \left( \frac{m_1 m_2}{r^2} \right) \]

\( F \) = gravitational force between two objects
\( m_1 \) = mass of first object
\( m_2 \) = mass of second object
\( r \) = distance between objects
\( G \) = universal constant of gravitation

- If the masses are measured in kilograms and the distance between them in meters, then the force is measured in Newtons.
- Laboratory experiments have yielded a value for \( G \) of

\[ G = 6.67 \times 10^{-11} \text{ Newton} \cdot \text{m}^2/\text{kg}^2 \]
Newton’s description of gravity accounts for Kepler’s laws and explains the motions of the planets and other orbiting bodies.

To make a ball move at a high speed in a small circle requires a strong pull.

To make the same ball move at a low speed in a large circle requires only a weak pull.

To make a planet move at a high speed in a small orbit requires a strong gravitational force.

To make the same planet move at a low speed in a larger orbit requires only a weak gravitational force.
Orbital Motion

- The law of universal gravitation accounts for planets not falling into the Sun nor the Moon crashing into the Earth.
- Paths A, B, and C do not have enough horizontal velocity to escape Earth’s surface whereas Paths D, E, and F do.
- Path E is where the horizontal velocity is exactly what is needed so its orbit matches the circular curve of the Earth.
Orbits follow any one of the family of curves called conic sections.
Gravitational forces between two objects produce tides in distant regions of the universe.
Understanding Tidal Forces

(a)
Billiard balls at rest

(b)
A short distance
A longer distance
A still longer distance
A short time later

(c)
From the perspective of the center ball
The yellow arrows indicate the strength and direction of the Moon’s gravitational pull at selected points on the Earth.
The yellow arrows indicate the strength and direction of the Moon’s tidal forces acting on the Earth.

From the perspective of the center of the Earth
This person is at low tide

Moon

This person is at high tide

Earth

This person is at high tide

Oceans

This person is at low tide
(a) **GRAVITATIONAL FORCE**
Bulge of water

(b) **CENTRIFUGAL FORCE**
Two resultant bulges of water

(c) **GRAVITATIONAL AND CENTRIFUGAL FORCE**
iClicker Question

If the Earth's axis were not tilted with respect to its orbital plane, then

A a mean solar day would be longer
B a sidereal day would be longer
C the tides would be much stronger
D there would be virtually no seasons
E the period of revolution and rotation would be equal
Key Words

• acceleration
• aphelion
• conic section
• conjunction
• deferent
• direct motion
• eccentricity
• ellipse
• elongation
• epicycle
• focus
• force
• geocentric model
• gravitational force
• gravity
• greatest eastern and western elongation
• heliocentric model
• hyperbola
• inferior conjunction
• inferior planet
• Kepler’s laws
• law of equal areas
• law of inertia
• law of universal gravitation
• major axis
• mass
• Neap and spring tides
• Newtonian mechanics
• Newton’s laws of motion
• Newton’s form of Kepler’s third law
• Occam’s razor
• opposition
• parabola
• parallax
• perihelion
• period (of a planet)
• Ptolemaic system
• retrograde motion
• semimajor axis
• sidereal period
• speed
• superior conjunction
• superior planet
• synodic period
• tidal forces
• universal constant of gravitation
• velocity
• weight
Vocabulary

- angle
- angular diameter (angular size)
- angular distance
- angular measure
- arcminute
- arcsecond
- astronomical unit (AU)
- Big Bang
- black hole
- degree (°)
- exponent
- galaxy
- gamma-ray burster
- hypothesis
- kiloparsec (kpc)
- laws of physics
- light-year (ly)
- megaparsec (Mpc)
- model
Vocabulary

- Antarctic and Arctic Circles
- apparent solar day
- apparent solar time
- autumnal equinox
- celestial equator
- celestial sphere
- circumpolar
- constellation
- declination
- diurnal motion
- ecliptic
- epoch
- equinox
- lower meridian
- mean solar day
- mean sun
- meridian
- meridian transit
- nadir
- north celestial pole
- positional astronomy
- precession
- precession of the equinoxes
- right ascension
- sidereal clock
- sidereal day
- sidereal time
- sidereal year
- south celestial pole
- summer solstice
- time zone
- tropical year
- Tropic of Cancer
- Tropic of Capricorn
- upper meridian
- vernal equinox
- winter solstice
- zenith
- zodiac
Vocabulary

- annular eclipse
- apogee
- eclipse
- eclipse path
- eclipse year
- first quarter moon
- full moon
- line of nodes
- lunar eclipse
- lunar phases
- new moon
- partial lunar eclipse
- partial solar eclipse
- penumbra
- penumbral eclipse
- perigee

- plane of the ecliptic
- saros
- sidereal month
- solar corona
- solar eclipse
- synchronous rotation
- synodic month
- third quarter moon
- totality
- total lunar eclipse
- total solar eclipse
- umbra
- waning crescent moon
- waning gibbous moon
- waxing crescent moon
- waxing gibbous moon