Chapter 2: Idea 1

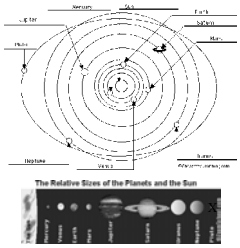
Copernican Astronomy

The Earth is not the center of the Universe.

Copernican Astronomy

- Today
  - Solar System model generally accepted
- Sun at the center of the Solar System
  - Moons orbit Planets
  - Planets orbit Sun
- Sun orbits center of Galaxy
- Galaxy moves – expanding Universe model

The Solar System



- But 500 years ago
  - Only "lunatics" thought and believed this.
- Look outside
  - It is "obvious" that ***we*** are not moving
  - But all the other celestial objects ***are***
- It looks as if we are stationary
  - At the center of everything
  - And everything else moves around us

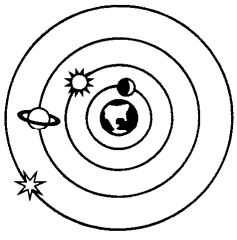
Geocentric Theory

- Look at the night sky
  - Appears to be a giant sphere with the Stars attached that rotates around the Earth once per day
- This is what the ancients believed
  - They called it the Celestial Sphere

Geocentric Theory

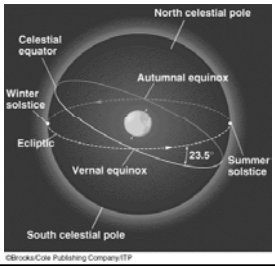
- Geocentric means "Earth-centered"
- In a Geocentric Theory
  - The Earth is at rest, which is consistent with our "common sense"
  - The Earth is at the center of the Universe
  - A very special place
  - Right where we humans think we belong…

A Simple Geocentric System



The Geocentric System

The Celestial Sphere



The Celestial Sphere

- Celestial Pole
  - part of sky above the Earth's poles
- Celestial Equator
  - part of sky above the Earth's equator
- Ecliptic
  - path Sun follows across the sky
- Tilted orbit
  - 23½° tilt

The Celestial Sphere

- This explained the motions of the Stars
  - Particularly the daily rotation (ex: Columbus, OH)

Overhead stars Circumpolar stars

- Had to add more spheres to explain
  - Motions of the Sun, the Moon, the Planets
  - Different than the Stars
- The word "planet"
  - Comes from the Greek word for "wanderer"

Ancient Greeks

Ancient Greeks

- Wanted a model of the Universe
  - to explain how it "really works"
- But they had some odd arbitrary ideas
  - that they imposed on the Universe
- This not science!!
  - Science lets nature tell us how it works
  - Greeks tried to tell nature how it should work

Ancient Greeks

- The Heavens are a region of "perfection"
  - So they never, ever change!
- Must use the "perfect" shapes to describe…
  - Circles and Spheres
- …everything in the heavens
  - is a smooth sphere that moves in a circle
  - always at a constant speed.

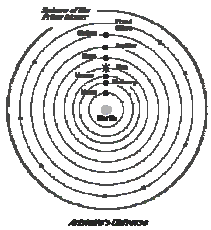
Ancient Greeks

- "Science" to the Greeks was a process of "saving the appearances"
  - Whether the theory was correct or not didn't matter as long as it fit the observations

Ancient Greeks

- Aristotle's system (350 BC)
  - Everything revolves around the Earth
  - 56 linked, homocentric spheres
    - "homocentric" means "same centers"
  - Prime Mover
    - Outermost sphere, moves all the the others

Ancient Greeks



Ancient Greeks

- A lovely system…but
  - It did not fit the Babylonian data
    - the most extensive and accurate at the time
  - It couldn't account for the changing size of the moon (8-10% change)
  - It couldn't account for the varying brightness of the planets
  - It couldn't account for just about anything!
    - But it was pretty to look at!

Claudius Ptolemy (~85 - ~165 AD)

- Greek born in Egypt (maybe)
- Astronomer
- Geographer

Ancient Greeks

Ptolemy

- Wanted a ***mathematical*** tool for calculating celestial motions
- Wanted accuracy for navigation and commerce
- But still committed to geocentric circles
  - He was still a Greek after all…he only cared about correct ***results***, not the correct ***theory***!

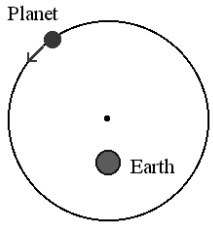
Ptolemy

- Ptolemy invented 4 devices (modifications)
  - Eccentric
  - Epicycle
  - Deferent
  - Equant
- Designed to improve accuracy
  - Better agreement between data and calculations
  - And maintain those "perfect" circles

Ptolemy's Devices

- Eccentric
  - Planets do not appear to move at a constant speed as seen from Earth
  - Ptolemy explained this by shifting the spheres
    - The center of planet-carrying sphere is not the center of the Earth
  - So a planet is not always the same distance away
    - Closer ⇒ Planet appears to move Faster
    - Further ⇒ Planet appears to move Slower

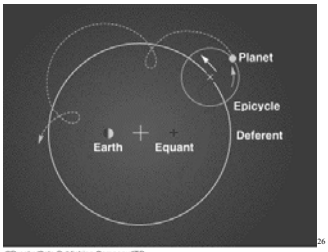
Ptolemy's Devices – Eccentric



Ptolemy's Devices

- Epicycle and Deferent
  - Planets sometimes appears to move backwards
    - Usually move from west to east
    - Sometimes stop and move east to west
    - Called "retrograde motion"
  - Ptolemy explained this with these devices:
    - The Epicycle is the planet-carrying sphere
    - The Deferent carries the Epicycle

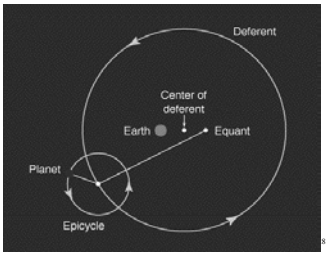
Ptolemy's Devices – Epicycle and Deferent



Ptolemy's Devices

- Equant
  - Planets do not appear to move at constant speed as seen from Earth
  - Ptolemy further explained this with the Equant
    - Place from which Planet's speed is uniform
    - Equidistant from Eccentric
    - Opposite earth
  - Saving appearance of uniform angular motion

Ptolemy's Devices - Equant



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Ptolemy's System

- Why all these contrived hoops?
  - Ptolemy wanted accuracy
    - Speed, Position, Time all must be correct
  - Yet he had to maintain those "perfect" circles
- Ptolemy's system last for 1400 years
- Why? Because it worked!!
  - Explained all the best known data
    - The Babylonian data

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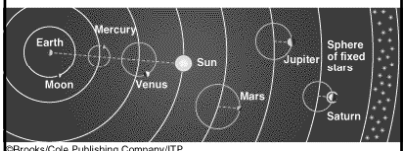
Ptolemy's System



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Ptolemy's System

- No better system came long until 1542
  - When Copernicus published his
- Ptolemy's system explained the current data
  - Cannot expect more
  - Better data did not come until after Copernicus
- His system was pretty good and easier to use than Aristotle's
  - But was inconsistent: not all of the devices were always used for every calculation

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Heliocentric Theory

- Heliocentric means "sun-centered"
- In a Heliocentric theory
  - The Sun is the center of planetary motion
  - Planets orbit the Sun
  - Planets rotate on their axis

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Historical Background

- This is an old idea
  - Ancients Greeks considered and rejected it
    - First proposed by Aristarchus
  - Their philosophy did not allow for a spinning, moving Earth
  - Too contrary to their way of thinking
    - "untenable" ⇒ cannot be maintained or defended
  - ***Contradicted their concept of "perfection"***

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Historical Background

- Around 1400 AD
  - Cracks in the Geocentric view began to show
- The Celestial sphere must be huge
  - Requires incredible rotational speed to move Stars around once per day
- God made an infinite Universe ⇒ no center
  - Center ⇒ same distance from some edge
  - If Universe was infinite, ***any*** spot could be the center, not just Earth!

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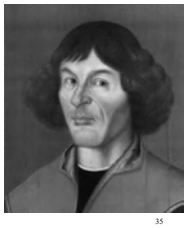
Nicolaus Copernicus (1473 – 1543)

- Born in Torun, Poland
- Lived to be 70!
  - very old for that time
- A well-educated man
  - Math, Law, Medicine, Astronomy, Theology
- Also a minor church official



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Nicolaus Copernicus

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Nicolaus Copernicus

- Nicolaus Copernicus
  - Church duties did not require lots of time
  - Started thinking about Astronomy (1510 AD)
- He analyzed Ptolemy's system
  - Conclusion: it was just too complicated
  - Did not like how the 4 devices were used
    - Thought it was inconsistent
    - ***Really*** disliked the Equant!

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Nicolaus Copernicus

- Invoked "Ockham's Razor" principle
  - If you have several possible explanations, the one that is the simplest is usually right
  - Subscribed to the "KISS" philosophy
    - ***K***eep ***i***t ***s***imple, ***s***tupid!
- This is the goal of science today
  - Prefer one simple explanation
    - for many different phenomena

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Nicolaus Copernicus

- To explain planetary motions
  - Ptolemy needed several contrived devices
  - Retrograde motion: Epicycles and Deferents
  - Varying Speeds: Equants and Eccentrics
- Copernicus used one simple idea
  - and turned it into a mathematical theory

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Simple Copernican Theory

- Sun fixed at the center of the Universe
- Stars attached to ***fixed*** Celestial Sphere
- Six known planets orbit Sun
  - In the same manner and direction
  - He kept the circular orbits, however
- Earth now just "third rock from the Sun"
  - No longer at a "special" place
  - Only the Moon orbits the Earth

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Simple Copernican Theory

- Explained Retrograde motion easily!
  - In fact, Copernicus's Theory ***requires it***!
- Outer planets move more slowly
  - Take more time to complete one orbit
- The inner planet laps the outer planet
  - Faster inner planets pass the slower outer ones
  - Outer ones appear to move backwards

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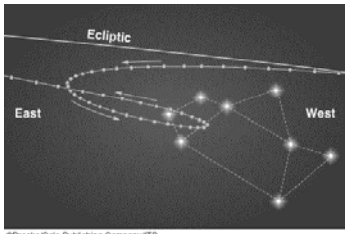
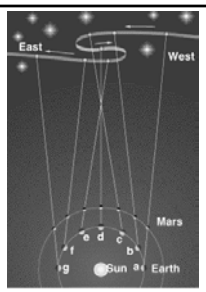
Retrograde Motion



Retrograde Motion

Heliocentric Explanation



Simple Copernican Theory

- Explained conjunctions
  - two objects appearing near each other in the sky
  - These occur naturally in Heliocentric systems
- Most common example
  - Eclipses
    - Sun and Moon "overlap"

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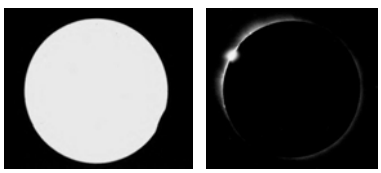
Conjunctions



An **Eclipse** involves a Moon-Sun **conjunction**

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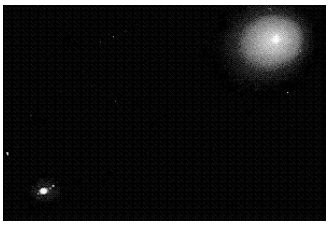
Conjunctions



A **conjunction** between Jupiter and Venus

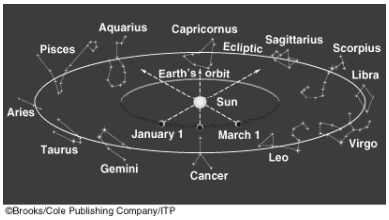
Simple Copernican Theory

- Explained apparent diurnal motion of Stars
  - "diurnal" means "daily" for our purposes
- Earth rotates on its axis once per day
  - As we watch from this rotating platform we see the Stars go by once per day
- But they are not moving around us
  - We are spinning under them

Simple Copernican Theory

- Explained the Ecliptic
  - The path of the Sun across the Celestial Sphere
- The axis of Earth's rotation is tilted
  - A 23½° tilt with respect to the orbit
    - The Sun is never more than 23½° from the equator

Ecliptic



Simple Copernican Theory

- Explained why Venus and Mercury are always seen near the Sun
  - Because they ***are*** near the Sun!
  - They are the two closest planets to the Sun
- In Ptolemy's Universe
  - They should be near the Sun sometimes and far away from it at other times

Simple Copernican Theory

- Predicted the order of the planets
  - Mercury, Venus, Earth, Mars, Jupiter, Saturn
  - The only six visible with the naked eye
  - The telescope had not yet been invented
- Correctly calculated the size of the Earth's orbit
  - The Earth is ~93 Million miles from the Sun

Simple Copernican Theory

- Copernicus used his new theory
  - and made some other calculations
  - Times and places of planetary appearances
- ***Results were not as good as Ptolemy's!*** (Ouch!!)
  - Better make some changes
  - An important clue to the right answer…

Modified Copernican Theory

- Copernicus reintroduced Ptolemy's devices
  - Used Epicycles, Deferents, and Eccentrics
  - ***No Equants!***
    - He hated them!
  - Used them fewer times
    - Down to a mere 46
  - However, he used them more consistently

Modified Copernican Theory

- The results: the ***same*** as Ptolemy's system
  - No better, no worse accuracy (@*##%&!!)
- But the calculations were ***much easier*** and took much less time to do
- So people used it
  - Even though most did not believe it was the correct theory

Modified Copernican Theory

- Copernicus finished his theory in 1530
  - Did not publish until 1543
  - He feared reprisals from Church
- On the day he died, it was published
  - "On the Revolutions of the Heavenly Spheres"
  - Legend has it he saw the first copy but did not notice the preface…

Modified Copernican Theory

- The book contained a preface
  - Saying that this was only a computational device to generate tables and calendars
  - ***Not*** a description of the ***real*** Universe
- The preface was believed to have been put in without his knowledge
  - By his assistant Osiander
  - Discovered by Kepler in 1609
  - Copernicus actually believed his theory was correct!

Reception of the Copernican Theory

- Initially the preface was accepted as is
  - Thought to be the author's own words
- The book even dealt with
  - Two types of possible objections to the theory
    - Scientific objections
    - Religious and Philosophical objections
  - These types of objections were considered to be on equal footing in most minds

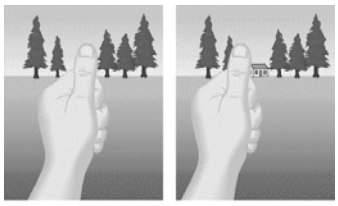
Reception of the Copernican Theory

- Scientific Objections
  - Theory contradicted accepted science
- Religious and Philosophical Objections
  - Theory contradicted many religious views

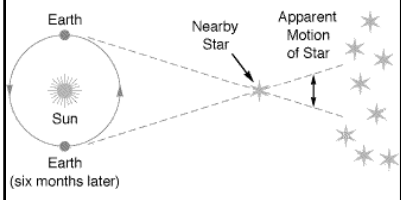
Scientific Objections

- Stellar Parallax
  - Apparent change in a Star's position due to the motion of the Earth
  - Should have been seen if Copernicus was right
  - But it was not observed!
    - Effect was too small to be seen with the naked eye
  - Not resolved until good telescopes came
    - Some 200 years later

Parallax



Stellar Parallax



Stellar Parallax

- Copernicus defended his idea
  - He believed the stars were 80 million miles away (even this was way too close)
    - This would have given a stellar parallax of 9.6 million miles
    - Too small to be seen with the naked eye!
    - That's why it wasn't observed
- Critics believed the stars were only at the orbit of Saturn
  - Should have easily seen stellar parallax, if it actually existed

Scientific Objections

- Stellar Size
  - Stars must be very distant: No Stellar Parallax
    - Yet they are easy to see with naked eye
    - If Copernicus was correct, how can we see the stars so easily….
  - Therefore, they must be huge!
    - Too big - much larger than the Sun – preposterous!!
  - Due to the wave nature of Light
    - And small eye aperture
      - the stars appear larger than when seen with a telescope
    - Not resolved for 300 years

Scientific Objections

- Physics
  - Moving Earth contradicted Aristotle's Physics
  - Aristotle predicted
    - There would be a strong breeze (3500 mph) which would destroy everything (hurricane ~ 140 mph)
    - Dropped objects would not fall straight down
    - A massive force was needed to keep Earth moving
      - There was no evidence of this force
    - Objects would fly off a spinning Earth
  - Not resolved until Newton's theories
    - 130 years later

Religious and Philosophical Objections

- Perfect Heavens
  - Recall the Greek's ideas about "perfection"
    - Circles and spheres
  - The heavens are perfect and unchanging
  - The Earth is neither
    - Volcanoes and erosion are two examples
    - So it cannot be part of the Heavens
    - ***So it cannot be just another planet***

Religious and Philosophical Objections

- The Bible and the Koran
  - Heliocentric theory contradicts literal readings of these religious documents
  - Contradicts their proclaimed cosmologies
    - Also known as "creation stories or myths"
  - So Copernicus's book was banned by Rome
    - Until 1835 (almost 300 years!)

Religious and Philosophical Objections

- Was tantamount to pagan sun-worshipping!
- These were important objections
  - That were neither made nor taken lightly
- Giordano Bruno
  - A monk who expanded Copernicus's ideas
  - Earth is like the planets so the planets are like Earth
  - Sun is a minor Star, so other planetary systems exist
  - Implies humans not unique in God's eyes
  - Burned at the stake for heresy

Copernican Theory

- Copernicus's Heliocentric Theory thrived
  - In spite of the many "reasonable" objections
  - But, results no better than Geocentric Theory
- Intellectually it was more appealing
  - A simple elegant idea
  - Showed that other ideas were possible
    - Paved the way for other theories

Copernican Theory

- The first step in the Scientific Revolution
- Before Copernicus
  - Art and Religion dominated Western thought
- After Copernicus
  - Science and Technology dominate
- He dethroned Greek science
  - For a more fruitful way

Compromise Theory

- Copernicus had a big problem
  - Most of his data were old and not very accurate
    - Those magnificent Babylonians!
- He died in 1543
  - Did not live to see the better data ~ 30 years later
  - Obtained by…

Tycho Brahe (1546 – 1601)

- Born in Knudstrup, Denmark
- Danish astronomer
- Greatest naked eye astronomer ever
  - No telescopes!

Tycho Brahe

Tycho Brahe


Tycho Brahe

- Son of Danish nobility
  - Kidnapped by childless uncle at age 1
  - Parents let the uncle keep him!
    - Talk about tough love!
- Started out studying Law and Philosophy
  - With an eye toward politics

Tycho Brahe

- Until he observed a solar eclipse in 1560
  - Switched to study of Math and Astronomy
- He had a sword duel in 1561
  - Over some point of mathematics
  - Lost the duel and his nose
  - Wore a false metal nose for rest of his life

Tycho Brahe

- Watched a Jupiter-Saturn conjunction in 1563
  - Occurred one month before the date predicted by Ptolemy's Theory, several days too soon using Copernican Theory
- Inspired him to build an observatory
  - To collect new, improved data
  - This is before telescopes were invented

Tycho Brahe

- Observed a "new" star in 1572
  - Coined the term "nova", meaning new star
  - Actually an exploding old star
  - Too faint to be seen before
- Published "Concerning the New Star"
  - Established his reputation as an astronomer
  - Showed that stars were much more distant than the Moon
  - Refuted idea of "perfect, unchanging" heavens

New Data

- Built his observatory in 1576
  - Near Copenhagen, Denmark
  - Sponsored by the King of Denmark

New Data

- Soon after, Brahe observed a comet
  - ***Proved*** it was beyond the Moon's orbit
  - Again showed heavens do change
    - Aristotle thought comets were atmospheric events
  - Comet's orbit was not a circle
    - Had a very elongated shape
    - Crossed several planetary orbits

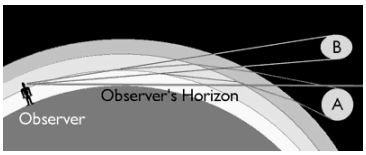
New Data

- Spent the rest of his life taking data
  - 20 years of excellent, accurate data
  - No telescopes, but he did have other tools
    - Sighting tubes
- Tracked the orbits of many celestial objects
  - Stars, Sun, Planets, Moon
- These data are his major contribution
  - to modern Astronomy

Tycho Brahe

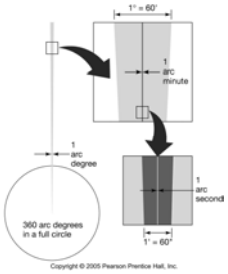
- Was the first to track the planets throughout their entire orbits
  - Most astronomers only recorded pieces of the orbits
- Calibrated his instruments nightly
  - Revolutionized astronomical instrumentation
- Was the first to account for atmospheric refraction
  - The bending of light rays in the atmosphere

Atmospheric Refraction



New Data

- He improved the accuracy of the data
  - His was ***5 times more accurate*** than the Babylonians
  - From 10 minutes of arc to 2 minutes of arc
  - To the limit of the unaided eye
- Measure very small angles in minutes
  - 1 minute of arc = $^1/_{60}$ of a degree
  - Move end of a yard stick $^1/_{50}$ of an inch
  - That is 2 minutes of arc!



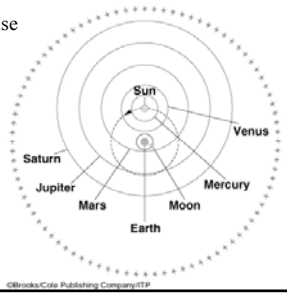
Compromise Theory

- Tycho Brahe published another book in 1583
  - Contained his theory of the Universe
- Called the "Compromise Theory"
  - All planets except Earth orbit the Sun
  - The Sun-Planets revolve around the Earth
  - The Moon also orbits the Earth
  - Celestial Sphere rotates around stationary Earth
    - Once every 24 hours

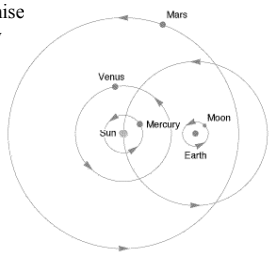
Compromise Theory

- A merging of Geocentric and Heliocentric
  - Avoids all objections due to moving Earth
  - Keeps relative ease of calculation
  - Eliminates planetary spheres
    - But keeps those @#$%* circular orbits
  - Recognized failure of Ptolemy's geocentric system
    - Once and for all!
- Did not last very long
  - Made obsolete by the work of Kepler – his assistant!

Compromise Theory



Compromise Theory



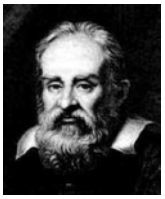
Tycho Brahe

- Died under bizarre circumstances in 1601
- At a "society" party
  - Impolite to excuse oneself to go to bathroom
  - Waited so long his bladder apparently burst
  - A long slow painful death
- On his death bed
  - Passed torch to his assistant and successor
  - Gave all that accurate data to Kepler
    - The one person who knew what to do with it!
    - But first, a short digression…

New Discoveries and Arguments

- By 1608…
  - Had observed 3 new astronomical events
    - Comet of 1576
    - Novas of 1572 and 1604
  - So heavens could and did change
    - Contradicts Aristotle's ideas of "perfection"
- Did the Earth move?
  - No reason it was different from other planets
  - But still no "proof" of Heliocentric theory

Galileo Galilei (1564 – 1642)



- Born in Pisa, Italy
- Known to posterity by his first name only
  - like Michelangelo
- No new theories - he was an observer

"**I do not feel obliged to believe that the same god who has endowed us with sense, reason and intellect has intended us to forgo their use.**" —Galileo

Galileo Galilei

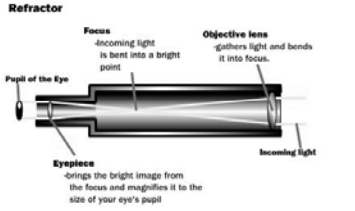
Galileo Galilei

- His career was a major turning point in the history of science
  - More on this later when we get to Newton…
- Galileo ***did not*** invent the telescope
  - It was invented in 1608 in Holland for military uses
  - Used for astronomy first by an Englishman, Thomas Harriot, to look at the moon for fun
  - Galileo did greatly improve it though
    - Increased its magnification by a factor of 30

Galileo Galilei

- He did something no one else had ever done
  - Used the telescope to observe the heavens
- Two new things here!
- Aimed telescope toward the sky in earnest
  - Mainly used for spying and military uses before
- Made systematic observations
  - Did not just ***look*** at the sky
  - He invents part of the Scientific Method

The basic refracting telescope



The basic refracting telescope

- A telescope has two general properties:
  1. How well it can collect the light from an object
  2. How much it can magnify the image of the object

The basic refracting telescope

A telescope's ability to collect light is directly related to the diameter of the lens (called the aperture) that is used to gather the light.

Generally, the larger the aperture, the more light the telescope collects and brings to focus, and the brighter the final image.

The basic refracting telescope

The telescope's magnification, its ability to enlarge an image, depends on the combination of lenses used.

The eyepiece performs the magnification. Since any magnification can be achieved by almost any telescope by using different eyepieces, the aperture is a more important feature than the magnification.

Galileo's Telescope

A Modern Small Refracting Telescope

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Galileo Galilei

- ***Made six major discoveries*** with his telescope
- Published them in a book in 1610
  - "The Starry Messenger"
- All of his astronomical discoveries
  - Have one important common factor…which we'll get to later

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Galileo's Discoveries

1. The Moon has mountains and craters
- Galileo even estimated the mountain heights
  - Using their shadows
- The Moon is not a perfect, smooth sphere
  - Contradicts Aristotle's notion of "perfection"

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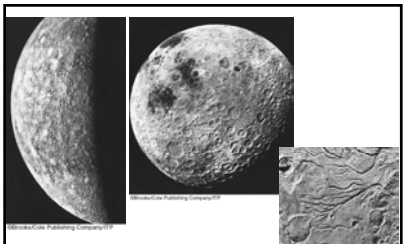

The Moon

Galileo's Discoveries

2. The Sun has dark spots called Sunspots
- These spots develop and disappear over a 22-year cycle
- The Sun is not a perfect, unchanging sphere
  - Contradicts Aristotle's notion of "perfection"

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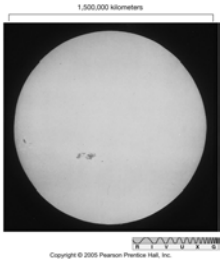
Sunspots



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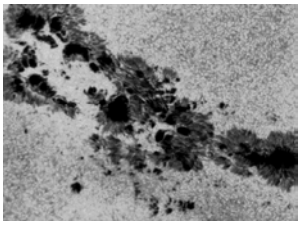
Sunspots



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Galileo's Discoveries

3. The Sun rotates on its axis
- The Sun spins on its axis
  - Much like the Earth does
- A motion not centered on the Earth
  - Contradicts Aristotle's Geocentric views

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Galileo's Discoveries

4. Jupiter has 4 moons
- Io, Europa, Callisto, Ganymede
  - Still called the Galilean Moons
- This showed that a moving Earth would not lose its Moon
  - Everyone agreed Jupiter was moving…
- Violated Aristotle's physics of moving objects
- Another motion not centered on the Earth

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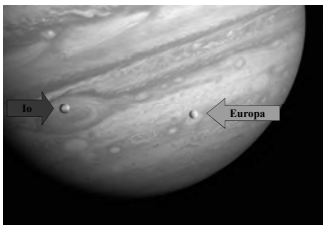
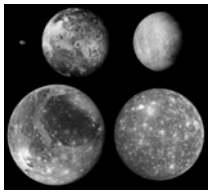
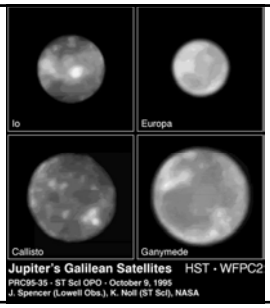
Galilean Moons



Galilean Moons plus one



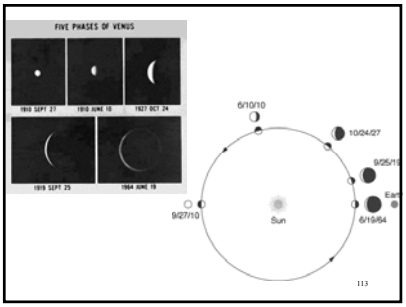
- Top
  - Amalthea, Io, Europa
- Bottom
  - Ganymede, Callisto
- Shown to scale



Galileo's Discoveries

5. Venus goes through phases

- Just like our moon does
- According to the Geocentric Theories
  - Venus is a permanent crescent
- Only Heliocentric Theory predicts phases
  - Phases only possible if Venus orbits Sun



Galileo's Discoveries

6. When he looked at the Stars, particularly in the Milky Way

- He saw more Stars, not bigger Stars!
  - Discovered the true nature of the Milky Way
- So the Stars must be incredible far away
  - Copernicus was right!
- Explained lack of observable Stellar Parallax

Galileo's Discoveries

- The common factor of the 6 discoveries?
  - They ALL support Copernicus!
  - And they ALL refute Aristotle/Ptolemy!
- These firmly and finally establish the Heliocentric Theory as fact
- Galileo becomes a public supporter of Copernicus
  - Uh-oh, the Church isn't going to like this! Remember Giordano Bruno…

Galileo Galilei

- Published a landmark book in 1632
  - "Dialogues on the Two Chief World Systems"
- A debate on the merits of the two systems
  - Geocentric versus Heliocentric
- A dialog among three characters
  - Two advocates – one for each system
  - And a moderator

Galileo Galilei

- The book was ***not*** objective
  - It was skewed toward the Heliocentric Theory
  - It openly supported Copernicus
- The book was published in Italian
  - Not the usually scholarly Latin
  - This made it available to the general public, not just the elite scholars

Galileo Galilei

- The advocate of the Geocentric system was named Simplicio
  - Approximate translation: the "Simpleton"
  - Often made to look foolish in the book
- Simplicio quoted the Pope verbatim!
  - Galileo put the Pope's words into the mouth of an idiot!
  - Talk about wearing a sign saying "Beat Me!"

Galileo Galilei

- Brought the wrath of the church against him
  - You don't publicly insult the Pope without expecting a little hostility from the Catholic Church…
- He was charged with heresy…
  - Even though he was a man of strong Catholic faith
  - Two of his daughters were nuns!!
- and with public humiliation of the Pope
  - Who thought Simplicio was a caricature of himself
  - The Pope took it ***very*** personally

Galileo Galilei

- Book was burned and placed on the Index
  - Not removed from the Index for over 300 years
- Convicted and forced to recant publicly
  - Under threat of torture by the Inquisition, even though he was a old, sick man
  - Placed under house arrest for the remainder of his life
    - A relatively "light" sentence for the Inquisition!!

The Scientific Revolution

- Began with Copernicus
  - Opposed for nearly 100 years
- Prevailed in large part due to Galileo
  - His careful, scientific method
  - His fight for what he thought was right
- He was willing to believe his own eyes
  - Not what he was told to believe
- Now, back to the story…

Kepler's Heliocentric Theory

- Brahe and Galileo used a modern approach
  - Brahe: accurate, extensive observations
  - Galileo: altered experimental conditions
    - To narrow down result
  - Rational, logical
    - The start of the Scientific Method
- ***Neither*** of these words describe our next guest…

Johannes Kepler (1571 – 1630)

- Born in Weil der Stadt, Württemberg, Holy Roman Empire (now known as Germany)
- A contemporary of Galileo
- Assistant to Tycho Brahe

Johannes Kepler

Johannes Kepler

- Kepler was a contemporary of Galileo
  - Born 8 years after Galileo
  - They never met, but did correspond occasionally
    - Galileo didn't care about Kepler's work
- Kepler was born 28 years after Copernicus
  - ***He was a firm supporter of the Copernican system***

Johannes Kepler

- Kepler had an incredibly miserable childhood
  - Contracted smallpox when he was 3, which crippled his hands and ruined his eyes for life
  - Father deserted the family soon after
  - Grandfather was the unpopular mayor of town
  - His family had few if any friends
  - He was given a religious education because he was not fit for more strenuous work

Johannes Kepler

- Childhood a huge effect on his personality
  - Emotional turmoil due to illnesses, real and imagined
- Referred to himself as a
  - "mangy dog" who tried to "keep the wolf from my door and the demons of the mind at bay"
  - Would be diagnosed with multiple mental/personality disorders if he were alive today

Johannes Kepler

- He was, however, a mathematical genius
  - Recognized in college
  - Led to teaching position in Science and Math
- However, he was a poor teacher
  - Lucky for us, but not for his students…
  - Gave him more time to study Astronomy

Johannes Kepler

- He was also a flake; something of a Mystic and a Numerologist
- Sought connections between geometry and numbers to explain the Universe
  - How it works
  - How it is arranged
  - Much like Pythagoras!

Pythagoras – an aside

- An ancient Greek
- Founded a secret mystical cult which had very strange rules
  - Couldn't poke a fire with an iron poker
  - Couldn't eat beans
  - Believed in reincarnation
    - Once attacked a man who was beating a dog
    - Told the man the dog was once his uncle!

Pythagoras – an aside

- Was a good scientist
  - Studied sound and harmonics
    - Shorter strings yield a higher pitch
- Believed in numerology based on whole numbers
- Studied mathematics
  - Discovered irrational numbers
    - Tried to keep these secret because he didn't like them (went against his beliefs)
- This was a man Kepler admired!

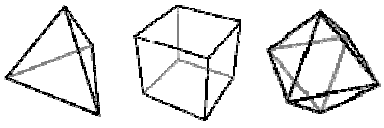
Kepler's Heliocentric System

- Example: the Planets
- He knew of 6 planets
  - Wondered why 6 and not some other number
- The Greeks had proven geometrically
  - That only 5 "Perfect solids" exist
  - Multi-faced figures with identical sides
  - Simplest example: a cube – 6 square sides

The Perfect Solids

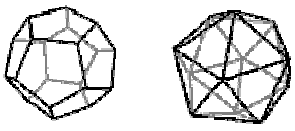
Perfect Solid	Number of Faces	Shape of Face
Tetrahedron	4	Equilateral Triangle
Cube	6	Square
Octahedron	8	Equilateral Triangle
Dodecahedron	12	Pentagon
Icosahedron	20	Equilateral Triangle

The Perfect Solids



Tetrahedron **Cube** **Octahedron**

The Perfect Solids



Dodecahedron **Icosahedron**

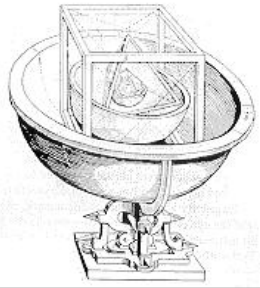
Kepler's Heliocentric System

- The 6 planets have 5 gaps between them
- To explain the Solar System
  - Kepler tried to fit the 5 perfect solids
  - between the 6 planetary spheres
- He was trying to explain the planetary order and their distances from the Sun

Kepler's Heliocentric System

- Saturn ⇐ Cube
- Jupiter ⇐ Tetrahedron
- Mars ⇐ Dodecahedron
- Earth ⇐ Icosahedron
- Venus ⇐ Octahedron
- Mercury

Kepler's Heliocentric System



Kepler's Heliocentric System

- He also knew that the planetary spheres
  - Were not homocentric with the Sun
  - Review: "homocentric" means "same center"
  - Same as for Ptolemy's and Copernicus's (modified) theories
- So he made an adjustment
  - ***Used spherical shells instead of spheres***
  - Adjusted the thickness of the shells to account for the planetary motions

Kepler's Heliocentric System

- And it worked!
  - Reproduced the planetary distances fairly well
- Published in "The Cosmic Mystery"
  - Detailed his scheme of the Universe
  - Established his reputation
    - As a Mathematician and an Astronomer
  - Opened the door to the job as Tycho's assistant

Johannes Kepler

- Made a promise to Tycho when he died
  - Kepler would use that wonderful data
  - And try to construct a system of the heavens based on Brahe's Compromise Theory
- Attacked the problem of the orbit of Mars
  - Most difficult orbit to reconcile with the data
  - The more accurate data showed errors in the existing tables of planetary positions

Johannes Kepler

- Worked on the Mars problem
  - 5 years before he abandoned a circular orbit
- Painstakingly constructed the orbit of Mars
  - From Tycho's great data
    - He believed Brahe's data was good to 2 arcminutes, Copernican Theory was only good to 10 arcminutes
  - Worked on it for 20 years!
- And worked out a new theory
- Discovered three important laws of Physics

Johannes Kepler

- All the while he had to endure
  - Fathering 13 children with two wives
  - Several job changes
    - Not all of them were willing changes
  - The death of his first wife
  - Successfully defending his mother against witchcraft charges.

Kepler's Laws of Planetary Motion

- After 20 years of analysis
  - Kepler notices some repeating patterns in the data
  - And figured out his laws of planetary motion
- These three laws are simple and useful
  - Still taught and used today
  - Published first two laws in 1609, last one in 1619

The First Law: The Ellipse Law

- The orbit of each planet is an ellipse with the Sun at one focus
- Kepler thought "outside of the box"!
  - discards the 2000 year obsession with circles
  - "If God did not want to make a circular orbit, then such an orbit was not mandatory"
- The off-center Sun
  - Provides the observed eccentricity in the orbit

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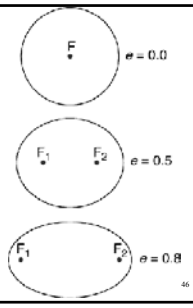
Ellipses



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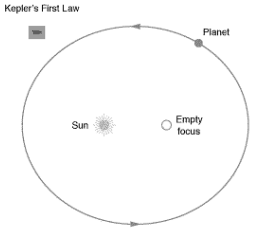
The First Law: The Ellipse Law



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The Second Law: The Area Law

- The line joining the Sun and the planet sweeps out equal areas in equal times as the planet orbits the Sun
- Describes planets varying speed and distance
  - Closer to Sun ⇒ Planet moves faster
  - Further from the Sun ⇒ Planet moves slower

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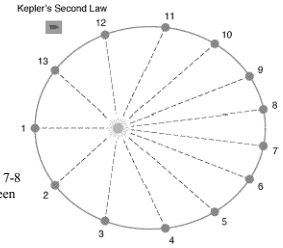
The Second Law: The Area Law



Area between 7-8 same as between 13-1

The Third Law: The Period Law

- The square of the period of revolution about the Sun is proportional to the cube of the average distance of the planet from the Sun
- The "period of revolution" is
  - the time for the planet to complete one orbit
  - For the earth, that is one year (365.25 days)

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The Third Law: The Period Law

$$T^2 = D^3$$

- *T*: Period in Years
  - time for one complete orbit
- *D*: average distance in Astronomical Units
  - 1 AU = average distance between Earth and Sun

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The Third Law: The Period Law

Planet	T	D	T^2	D^3
Mercury	0.24	0.39	0.058	0.059
Venus	0.62	0.72	0.38	0.37
Earth	1.00	1.00	1.00	1.00
Mars	1.88	1.53	3.53	3.58
Jupiter	11.9	5.21	142	141
Saturn	29.5	9.55	870	871

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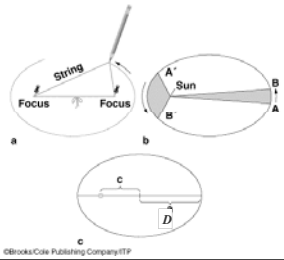
Kepler's Laws



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Johannes Kepler

- Finished life working on various projects
  - Observed Jupiter's moons
    - And coined the term "satellite"
  - Used the newly invented logarithms
    - First important use of this valuable mathematical tool
      - Considered to be a "toy" before his usage
  - Almost invented the Calculus
    - Calculated volume of wine for daughter's wedding
    - Thought we was being cheated – he was right!

Johannes Kepler

- Wrote the first science fiction story
  - Called "Somnium"
  - About a man who travels to moon in a dream
- Kepler was the right guy in the right place
  - No one else have could have done it
    - Had both the skill and the perseverance
    - To handle Tycho's data
  - A mystic and a brilliant mathematician

Leftover Problems

- Slow acceptance
  - Ignored by Galileo, who still believed in circles
- What made the planets move?
  - Kepler claimed it was the Sun's magnetism (wrong)
- Couldn't explain why the orbits were ellipses
  - Needed Newton's gravity theory

The March of Time

Scientist	Time
Aristotle	350 BC
Ptolemy	150 AD
Copernicus	1543 AD
Brahe	1583 AD
Galileo	1632 AD
Kepler	1609 AD

~ 500 years

~ 1400 years

~ 100 years

Important Concepts Changed!

- Earth is not at the center
  - We're not that special after all!
- The heavens were changing
  - So much for the Greek's concept of "perfection"
- We don't need no stinking circles!