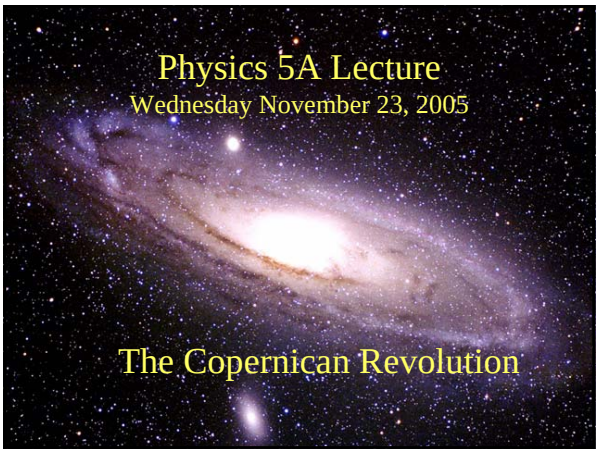



## The Scientific Revolution

Medieval cosmology, based on the work of the Alexandrian Greek astronomer **Ptolemy**, was consistent with common sense:

The earth doesn't appear to move.

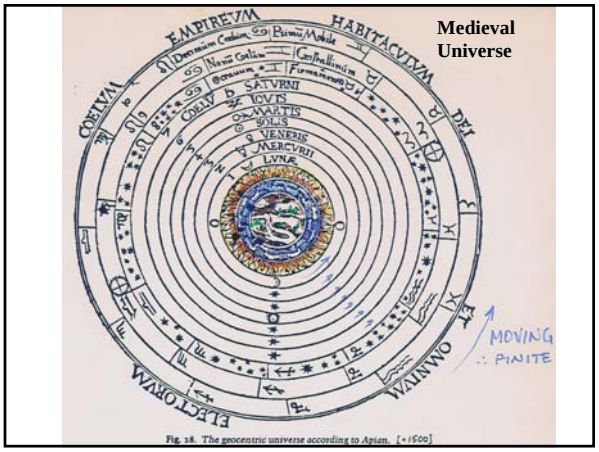
The stars pass overhead every night, the sun every day.

**Copernicus**'s heliocentric model overthrew common sense. A harmonious theoretical system was more important to Copernicus than common sense.

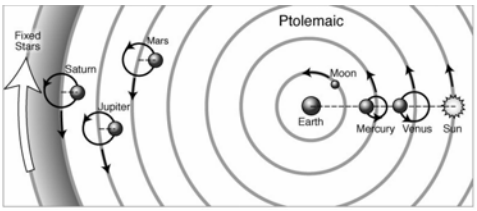
**Galileo**'s observations of the phases of Venus, moons of Jupiter, moon's rough landscape, etc., convinced nonscientists too, but did not actually prove the earth moved. " Philosophy is written in this grand book, the universe,…in the language of mathematics."

For **Kepler**, mathematical regularity was an explanation because God spoke in mathematics. His laws of planetary motion convinced astronomers.

**Newton** completed the scientific revolution begun by Copernicus by creating the concept of gravity and tying together the orbits of the planets with the motions of particles and the falling of apples -- quantitatively.



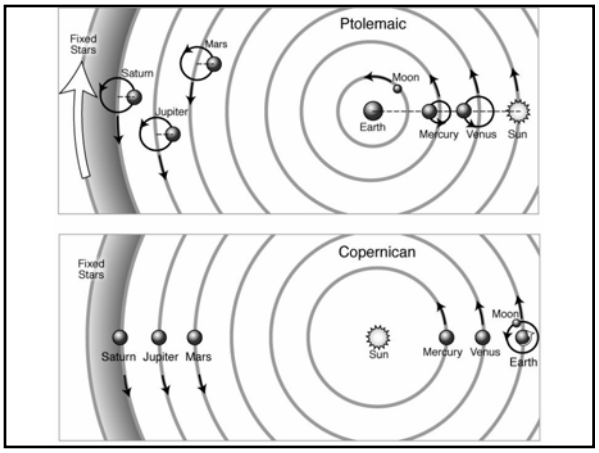

## PTOLEMY'S PICTURE OF PLANETARY MOTION




Mercury and Venus are never far from the sun. They move on epicycles centered on a line connecting the Earth and the Sun.

The outer planets sometimes move backwards for a while ("retrograde motion"), which is accounted for in the Ptolemaic system by having them also move on epicycles.

**Copernicus** (1473-1543) became dissatisfied with this system because it was not geometrical enough. The order of the planets and their distances were arbitrary, and all but the Moon were linked to the Sun: the centers of the epicycles of Mercury and Venus lie on the line between the Earth and the Sun, and the retrograde motions of Mars, Jupiter, and Saturn occur when they are opposite the Sun. Copernicus showed that all these puzzling elements disappear when the Sun is taken as the center.

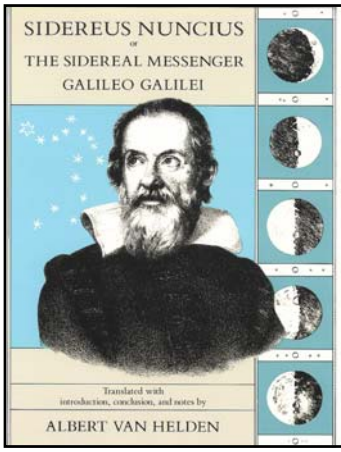



## REACTIONS TO COPERNICUS

"Copernicus affirmeth that the earth turneth about and that the sun standeth still in the midst of the heavens, by help of which false supposition he hath made truer demonstrations of the motions and revolutions of the celestial spheres, than ever were made before." – Astronomer Thomas Blundeville (1594)

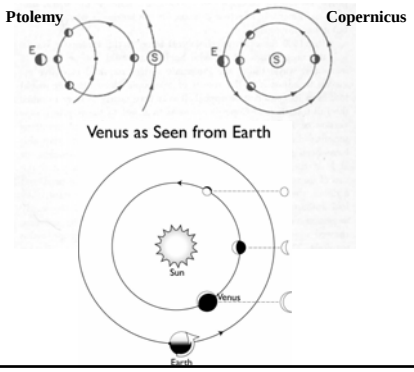
"People gave ear to an upstart astrologer who strove to show that the earth revolves, not the heavens or the firmament, the sun and the moon. This fool wishes to reverse the entire science of astronomy, but sacred Scripture tells us (Joshua 10: 13] that Joshua commanded the sun to stand still, and not the earth." – Martin Luther

"No one in his senses, or imbued with the slightest knowledge of physics will ever think that the earth, heavy and unwieldy from its own weight and mass, staggers up and down around its own center and that of the sun; for at the slightest jar of the earth, we would see cities and fortresses, towns and mountains thrown down." – Philosopher Jean Bodin (1628)




**Galileo** (1564-1642) learned that the telescope had been invented and that it had a convex lens in front of a concave one. He figured out how it worked, and learned how to make much better telescopes. He used them to study the heavens, and discovered that the Milky Way was made of countless stars, that the Sun had sunspots, that Jupiter had four moons which moved from night to night, and that the Moon had valleys and mountains. He was even able to figure out how high the Moon's mountains were by studying their shadows. At left are some of Galileo's sketches of the moon and Jupiter with its moons, from his book ***Sidereus Nuncius*** (1610), the first scientific best seller!

Copernicus had said in ***De Revolutionibus*** that if it were possible to see the phases of Venus, one could tell whether Ptolemy's system was correct. Galileo used his telescope to do the observations in 1610-11. Ptolemy was wrong!




## John Donne (1572-1631)

The new Philosophy calls all in doubt,
The Element of fire is quite put out;
The Sun is lost, and th'earth, and no man's wit
Can well direct him where to look for it.
And freely men confess that this world's spent,
When in the Planets, and the Firmament
They seek so many new; then see that this
Is crumbled out again to his Atomies
'Tis all in pieces, all coherence gone;
All just supply, and all Relation;
Prince, Subject, Father, Son, are things forgot...

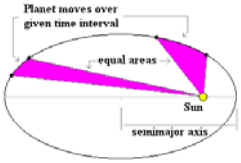
*Anatomy of the World, The First Anniversary*
(first published 1611), l. 205+

## KEPLER'S LAWS OF PLANETARY MOTION

Using the superb observations of Tycho Brahe, Kepler discovered

**1. Elliptical orbit law**: The planets orbit the sun in elliptical orbits with the sun at one focus.

**Note that the planetary orbits are nearly circular – but comets also follow Kepler's laws and their orbits are often as elliptical as the figure at right.**




**2. Equal-area law**: The line connecting a planet to the sun sweeps out equal areas in equal amounts of time.

**3. Law of periods**: The time ***T*** required for a planet to orbit the sun, called its period, is proportional to the long axis of the ellipse ***a*** raised to the 3/2 power. The constant of proportionality *c* is the same for all the planets: $\boldsymbol{T} = c\,\boldsymbol{a}^{3/2}$.

## Newton and the Scientific Revolution

Medieval astronomy rested on the idea that the motions observed in the heavens actually take place, and that the earth is stable. **Modern science was born in the denial of common sense.** Copernicus became dissatisfied with the Ptolemaic system because it was not geometrical enough. Galileo's observations with the telescope of the phases of Venus disproved the Ptolemaic system. They fit more smoothly into the heliocentric system, but they did not prove that it was true. Kepler's three laws of planetary motion further showed how economically the motion of the planets could be described in the heliocentric system, but if the Earth really were rotating on its axis and hurtling through space, why do we not perceive the motion? Galileo and Descartes tried to answer this question by reformulating the theory of motion, so that not motion but ***change*** in motion was what must be accounted for. Newton completed this reformulation.

Isaac Newton was born in 1642, and by 1666 he had invented calculus and begun his development of mechanics. But chemistry and alchemy dominated his interests until 1684, when Edmund Halley's question about the orbit of an object moving under the influence of gravity as an inverse-square-law force drew Newton back to mechanics. Newton's ***Mathematical Principles of Natural Philosophy***, published in 1687, was immediately recognized as a monumental work – perhaps the most influential in the entire history of science. By describing the motion of all bodies, on Earth and in the heavens, as arising from the same principles, he simultaneously provided a unified conception of nature and provided an answer to all the objections to the heliocentric system. Moreover, no one could fail to be impressed by the astounding precision with which Newton's system predicted such phenomena as the tides and the motions of the planets and comets.

## Changing Cosmologies

| Size R<br>Age T<br>Center | Composition | Unifying Ideas | God's role? |
|---|---|---|---|
| **Medieval Cosmos** | | | |
| Finite R<br>Finite T<br>Geocentric | Sublunary:<br>Earth, Water, Air, Fire<br>Heavens: Ether | Circular motion<br>Great Chain of Being | Prime mover, Hierarch, Saviour |
| **Newtonian Cosmos** | | | |
| Infinite R?<br>Infinite T?<br>No center | Atoms, Void<br>Ether? | Deterministic mechanics<br>Universal gravitation | Clockmaker |
| **Modern Cosmos** | | | |
| $R = 10^{28}$ cm<br>$T = 10^{10}$ yr<br>Homogeneous & Isotropic | Atoms<br>quarks, electrons<br>Radiation<br>Dark Matter<br>Vacuum | Gravity = space curvature<br>Nondeterministic quantum theory<br>Evolution | Before the Big Bang?<br>Immanent? |

**After the Copernican-Newtonian Revolution, the Medieval Cosmos was taught only as history, never again as scientific truth**

| | | | |
|---|---|---|---|
| Finite R<br>Finite T<br>Geocentric | Sublunar<br>Earth, W<br>Air, Fire<br>Heavens | ar motion<br>Chain of | Prime mover,<br>Hierarch,<br>Saviour |

Overthrowing Revolution

Newtonian Cosmos

| | | | |
|---|---|---|---|
| Infinite R?<br>Infinite T?<br>No center | Atoms, Void<br>Ether? | Deterministic mechanics<br>Universal gravitation | Clockmaker |

**But since Newton, all scientific revolutions in physics have been encompassing revolutions**

Newtonian Cosmos

| | | | |
|---|---|---|---|
| Infinite R?<br>Infinite T?<br>No center | Atoms, Void<br>Ether? | Deterministic mechanics<br>Universal gravitation | Clockmaker |

Encompassing Revolution

Newtonian physics

v/c

Relativity

Quantum ψ Mechanics

Modern Cosmos

| | | | |
|---|---|---|---|
| $R = 10^{29}$ cm<br>$T = 10^{10}$ yr<br>Homogeneous & Isotropic | Atoms<br>quarks, electrons<br>Radiation<br>Dark Matter<br>Vacuum | Gravity = space curvature<br>Nondeterministic quantum theory<br>Evolution | Before the Big Bang?<br>Immanent? |

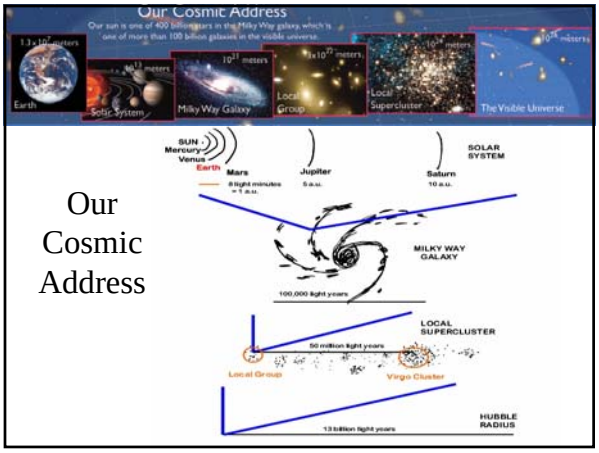
## Encompassing Revolutions

A new scientific theory ENCOMPASSES an old one when the new theory is valid for a wider class of phenomena, and the new theory reduces to the old one for a subset of these phenomena – that is, the two theories make the same predictions (to some specified accuracy).

EXAMPLE: Einstein's Theory of Relativity makes the same predictions for motion as Newton's theory whenever the speeds are slow compared to the speed of light, and gravity is not too strong. All the planets in the solar system move very slowly compared to the speed of light, and gravity is relatively weak. Therefore relativity makes the same predictions for the motions of the planets as Newton's theory, except for some very small differences in the motions of the fastest planets that orbit closest to the sun.

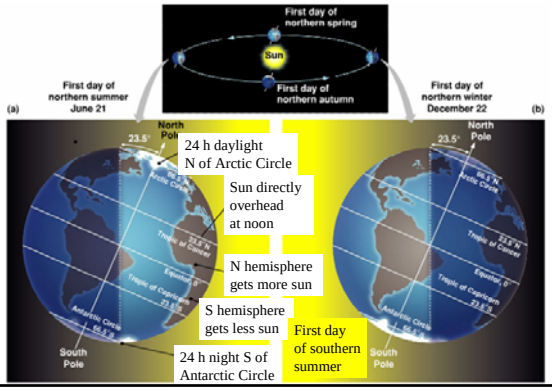
## The highest grade of truth

Charles Misner has pointed out a deep insight about scientific truth: the only sort of theory we can know to be "true" is one which has been shown to be false – in the sense that its limitations are known. As philosophers of science from Hume to Popper have emphasized, we can never prove that a scientific theory is true, since there is always the possibility that new data will be discovered that disprove it. But when a scientific theory has been encompassed by a more comprehensive theory that itself has been well tested, we can have considerable confidence that the encompassed theory is "true" within its known limits. This is the highest grade of scientific truth that is available.

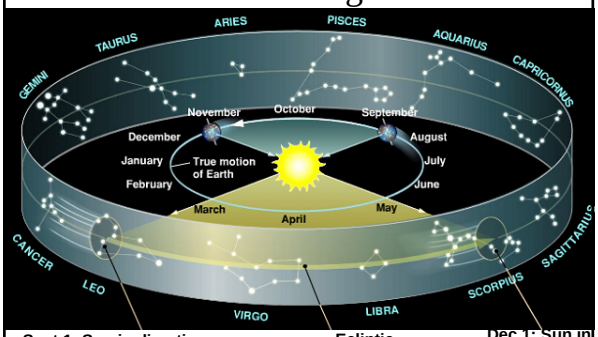



Our Cosmic Address

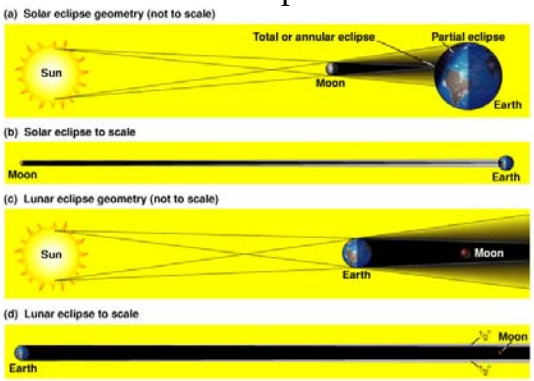
## Seasons




## The Sun Moves Against the Stars




## Eclipses




## Mini-Quiz

Q1. The reason there are seasons is that
A. The earth is closer to the sun in summer than in winter
B. The earth's axis is tilted

Q2. When it is summer (the warmest season) in the N hemisphere
A. It is also summer in the S hemisphere
B. It is winter in the S hemisphere

Q3. Match correctly:

| | |
|---|---|
| A. Solar eclipse | 1. Full moon |
| B. Lunar eclipse | 2. New moon |