The Scientific Revolution

From Copernicus to Einstein

The Old Astronomy

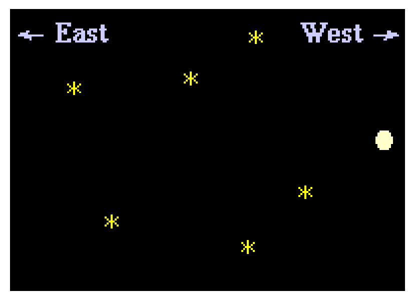
- The view of the Universe held by astronomers as little as 500 years ago differed substantially from our modern view.

2

The Apparent Motion of Planets on the Celestial Sphere

- Two observations concerning the planets were very difficult to explain for astronomers of the Middle Ages:
  – The usual motion of planets as they "wandered" on the celestial sphere was eastward against the background stars. However, at times the planets moved westward; this was termed "Retrograde Motion" and was difficult to explain.
  – The planets were observed to be brighter at certain times than others. This varying brightness was also a challenge to explain.
- Both retrograde motion and varying brightness are illustrated in the next animation.

3



4

HTML Version of Retrograde Motion

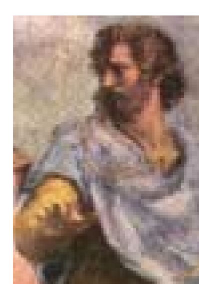
Uniform Circular Motion

- A major reason for the difficulty of explaining these features was the dominance of the Greek philosopher Aristotle on medieval thought.
  – This philosophy held that the heavens were more perfect than the Earth, and that objects in the heavens were unchanging.
  – As part of this philosophy, it was believed that the only motion permitted objects in the heavens was *uniform circular motion* (motion at constant angular speed on a circle), because such motion brought one back cyclically to the starting point and therefore was (in a sense) unchanging.

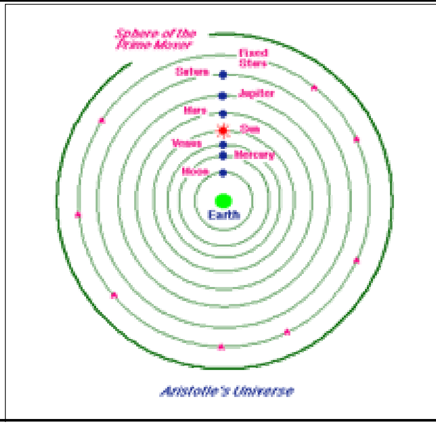
5

Aristotle's View of the Universe

- Aristotle proposed that the heavens were composed of fifty-five concentric, crystalline spheres to which the celestial objects were attached and which rotated at different velocities, with the Earth at the center.

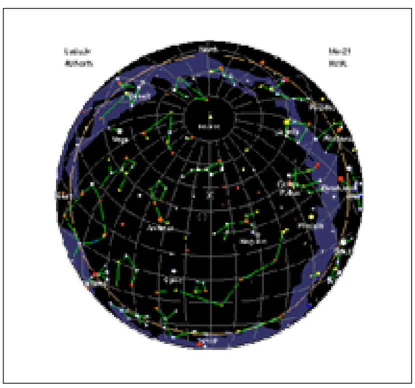


6



Aristotle's Prime Mover

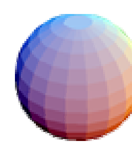
- According to Aristotle, there was an outermost sphere that was the domain of the "Prime Mover". The Prime Mover caused the outermost sphere to rotate at constant angular velocity, and this motion was imparted from sphere to sphere, thus causing the whole thing to rotate.



HTML Version of Celestial Sphere

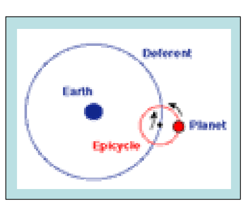
Troubling Observations

- By adjusting the velocities of these concentric spheres, many features of planetary motion could be explained.
- However, two observations could not be explained:
  - Varying planetary brightness
  - Retrograde motion.



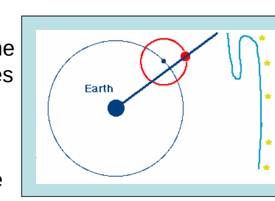
Solution: Epicycles and Deferents

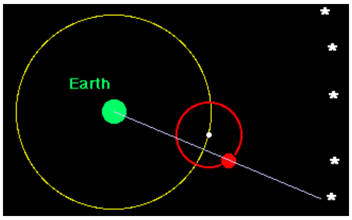
- The "solution" to these problems came in the form of an absurd but clever proposal: planets were attached, not to the concentric spheres themselves, but to circles attached to the concentric spheres, as illustrated by this diagram.



Movement of the Planets

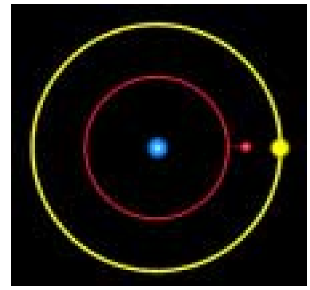
- As the center of the epicycle moves around the deferent, the planet moves around the epicycle. The apparent position of the planet on the celestial sphere is indicated by the line drawn from the earth through the planet. The apparent path against the background stars is indicated by the blue line.





HTML Version of Retrograde Motion

13

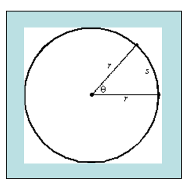


HTML Version of Retrograde Motion

14

The Result: Uniform Circular Motion

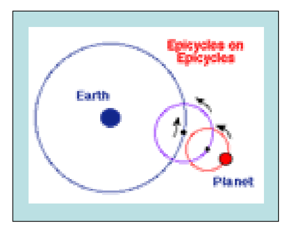
- With this model, it is possible to have retrograde motion and variations in brightness.
- Thus, the idea of uniform circular motion is saved (at least in some sense).



15

Further Refinements

- However, in practice, even this was not enough to account for the detailed motion of the planets in the celestial sphere. In some cases, epicycles were themselves placed on epicycles.



16

Guiding Principles

- The ancient astronomers devised this elaborate scheme because they never questioned three principles that we now know to be wrong:
  - All motion in the heavens is uniform circular motion.
  - The objects in the heavens are made from perfect material and cannot change their intrinsic properties (e.g., their brightness).
  - The Earth is at the center of the Universe.

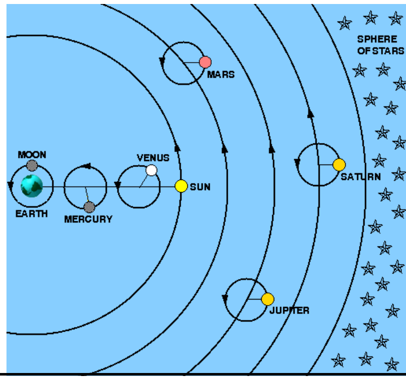
17

Ptolemy

- Prevailing ideas concerning uniform circular motion and epicycles were catalogued by Ptolemy in 150 A.D. in his book the *Almagest.* His picture of the structure of the Solar System has come to be called the "Ptolemaic Universe".

18

The Ptolemaic Universe



Medieval Representation of Ptolemaic Universe

Comfort, Reassurance, Stability

- The universe of Ptolemy offered comfort, reassurance, and stability. By placing the earth in the center, mankind was assured of its importance in God's plan. The individual could locate God, and knew the soul's destination would be above or below. Mankind was pulled downward by sin; but Heaven was the source of a divine power which could triumph over the inevitable corruption and decay of earthly things, and lift the soul to an afterlife in heaven.

The Influence of Thomas Aquinas

- By the Middle Ages, such ideas took on a new power as the philosophy of Aristotle (newly rediscovered in Europe) was wedded to Medieval theology in the great synthesis of Faith and Reason undertaken by philosopher-theologian Thomas Aquinas (1225-1274).

Medieval View of the Universe

- The Prime Mover of Aristotle's universe became the God of Christian theology.
- The outermost sphere of the Prime Mover became identified with the Christian Heaven
- The position of the Earth at the center of it all was understood in terms of the concern that the Christian God had for the affairs of mankind.

Religious Dogma

- Consequently, ideas largely originating with pagan Greek philosophers were incorporated into the Catholic church and assumed the power of religious dogma: to challenge this view of the Universe was not merely a scientific issue; it became a theological one as well, and subjected dissenters to the considerable and not always benevolent power of the Church.

Development of Modern Astronomy

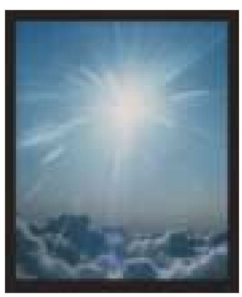
- The development of modern astronomy from the old astronomy/astrology was a long process with multiple steps.
  - It begins with the introduction of the Sun-centered Solar System by Copernicus.
  - It concludes with Newton's synthesis of the laws of motion in the heavens and the Earth, and Einstein's revision of Newton's ideas in the Relativity Theory.

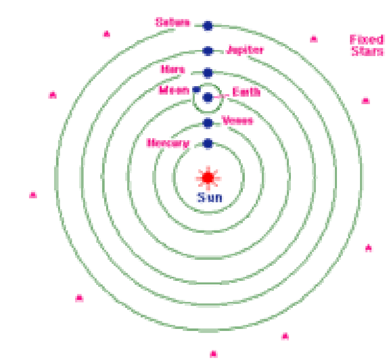
The Copernican Model: A Sun-Centered Solar System

- The Earth-Centered Universe of Aristotle and Ptolemy held sway on Western thinking for almost 2000 years. Then, in the 16th century a new idea was proposed by the Polish astronomer Nicolas Copernicus (1473-1543).

The Heliocentric System

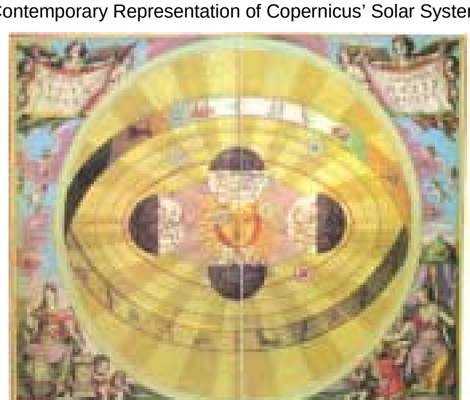
- In *On the Revolutions of the Heavenly Bodies* (published as he lay on his deathbed), Copernicus proposed that the Sun, not the Earth, was the center of the Solar System. Such a model is called a *heliocentric system*.





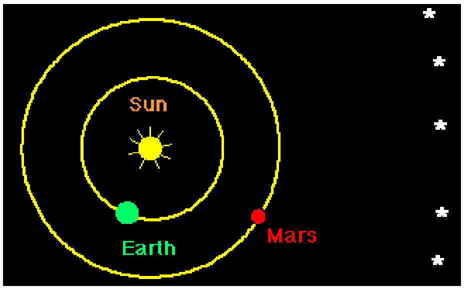
Copernicus' Universe

Contemporary Representation of Copernicus' Solar System



Retrograde Motion and Varying Brightness

- By banishing the idea that the Earth was the center of the Solar System, the Copernican system immediately led to a simple explanation for both the varying brightness of the planets and retrograde motion:
  - The planets in such a system naturally vary in brightness because they are not always the same distance from the Earth.
  - The retrograde motion could be explained in terms of geometry and a faster motion for planets with smaller orbits, as illustrated in the following animation.

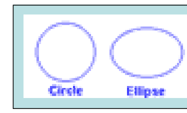


HTML Version of Copernican Retrograde Motion

31

Copernicus and the Need for Epicycles

- Copernicus was able to rid himself of the long-held notion that the Earth was the center of the Solar system, but he did not question the assumption of uniform circular motion.
  - Since the orbits of the planets are not circles but ellipses, Copernicus could not explain all the details of planetary motion without epicycles.
  - The difference was that the Copernican system required fewer epicycles than the Ptolemaic system.



32

The Copernican Revolution

- Copernicus was an unlikely revolutionary. He feared ridicule and disfavor: by his peers and by the Church, which had elevated the ideas of Aristotle to the level of religious dogma.
- However, he set in motion a chain of events that would produce the greatest revolution in thinking that Western civilization has seen.
- A crucial ingredient in the Copernican revolution was the acquisition of more precise data on the motions of objects on the celestial sphere

View Comparison between Ptolemaic and Copernican Systems

33

Tycho Brahe

- A Danish nobleman, Tycho Brahe (1546-1601), made important contributions:
  - He built the finest astronomical observatory in Europe.
  - He devised the most precise instruments available before invention of the telescope.
  - He compiled extensive data on the planet Mars, which proved crucial to Kepler in demonstrating that the orbit of Mars was not a circle but an ellipse.

34

Uraniborg Astronomical Observatory

35

Brahe's Observations

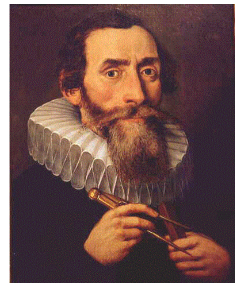
- Brahe proposed a model of the Solar System that was intermediate between the Ptolemaic and Copernican models (it had the Earth at the center). It proved to be incorrect, but was the most widely accepted model of the Solar System for a time.

36

Brahe’s Solar System

37

Johannes Kepler



- The next great development in the history of astronomy was the theoretical intuition of Johannes Kepler (1571-1630), a German who went to Prague to become Brahe's assistant.

38

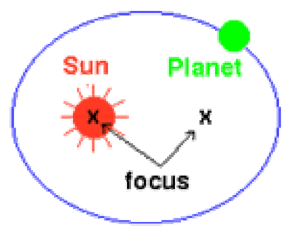
Kepler’s *Three Laws of Planetary Motion*

- After a long struggle, Kepler was forced to realize that the orbits of the planets were not the circles demanded by Aristotle and assumed implicitly by Copernicus, but were instead the "flattened circles" that geometers call ellipses.

39

Kepler’s First Law

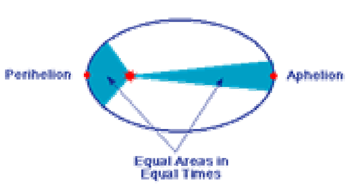
I. The orbits of the planets are ellipses, with the Sun at one focus of the ellipse.



40

Kepler’s Second Law

II. The line joining the planet to the Sun sweeps out equal areas in equal times as the planet travels around the ellipse.



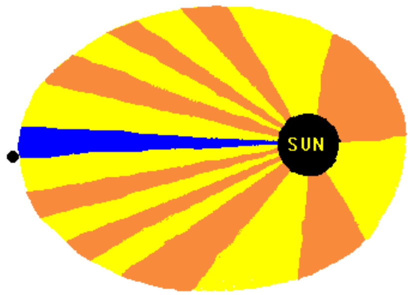
41

Kepler’s Third Law

III. The ratio of the squares of the revolutionary periods for two planets is equal to the ratio of the cubes of their semi major axes:

$$\frac{P_1^2}{P_2^2} = \frac{R_1^3}{R_2^3}$$

42

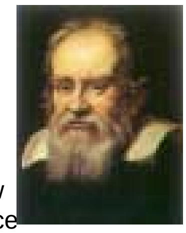


HTML Version of Kepler's Law

43

Galileo Galilei

- Galileo Galilei (1564-1642) provided the observations necessary to prove the Copernican hypothesis and laid the foundations for understanding two physical phenomena: dynamics (how objects moved on the surface of the earth) and gravity.



44

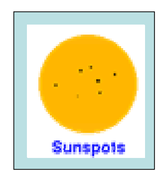
The Telescope

- Galileo was the first to use the telescope to study the heavens systematically. What he observed in the heavens rocked the very foundations of Aristotle's universe and the theological-philosophical worldview that it supported.

45

Sunspots

- Galileo observed the Sun through his telescope and saw dark patches (*sunspots*) that moved, indicating that the Sun was rotating on an axis.
  - These "blemishes" on the Sun were contrary to the doctrine that the heavens were made from a perfect, unchanging substance.
  - The rotation of the Sun made it less strange that the Earth might rotate on an axis too.

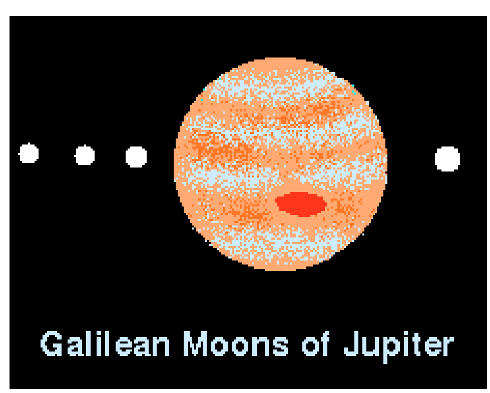


46

The Moons of Jupiter

- Galileo observed four points of light that changed their positions with time around the planet Jupiter. He concluded that these were objects in orbit around Jupiter. Indeed, they were the four brightest moons of Jupiter.
- These observations demonstrated that a planet could have moons circling it that would not be left behind as the planet moved around its orbit.

47

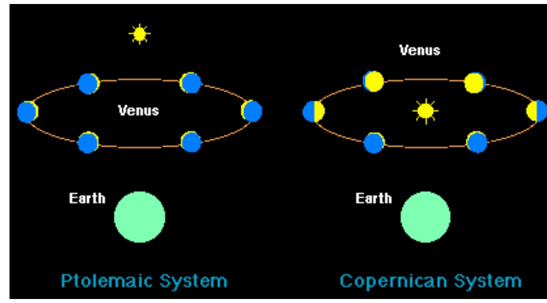


48

The Phases of Venus

- Galileo used his telescope to show that Venus went through a complete set of phases, just like the Moon. This observation confirmed the Copernican system.
  - In the Ptolemaic system Venus should always be in crescent phase as viewed from the Earth because as it moves around its epicycle it can never be far from the direction of the sun (which lies beyond it).
  - But in the Copernican system Venus should exhibit a complete set of phases over time as viewed from the Earth because it is illuminated from the center of its orbit.

49



50

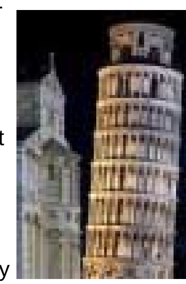
Empirical Evidence Supports Copernican System

- This was the first empirical evidence (almost a century after Copernicus) that allowed a definitive test of the two models. Until that point, both the Ptolemaic and Copernican models described the available data.
  - The primary attraction of the Copernican system was that it described the data in a *simpler* fashion
  - But here was conclusive evidence that not only was the Ptolemaic universe more complicated, but it was also *incorrect*.

51

Galileo and the Leaning Tower

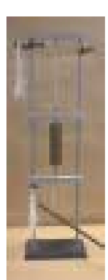
- Galileo made extensive contri-butions to our understanding of the laws governing the motion of objects. It is unlikely that he himself dropped two objects of very different weight from the Leaning Tower of Pisa to prove that they would hit the ground at the same time. But he understood the principle involved and probably did similar experiments.



52

Galileo and the Concept of Inertia

- Perhaps Galileo's greatest contribution to physics was his formulation of the concept of *inertia*: an object in a state of motion possesses an ``inertia'' that causes it to remain in that state of motion unless an external force acts upon it.



53

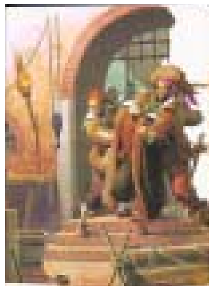
Frictional Force

- Aristotle had believed that objects in motion remained in motion only when a force acted constantly upon them. But he failed to account for a hidden force: the *frictional force* between the surface and the object.
- Galileo realized that as the frictional forces are decreased, the object moves further and further before stopping.

54

Galileo and the Church

- Galileo's challenge of the Church's authority through his assault on the Aristotelian conception of the Universe eventually got him into deep trouble with the Inquisition. Late in his life he was forced to recant publicly his Copernican views and spent his last years essentially under house arrest.



55

Isaac Newton

- Sir Isaac Newton (1642-1727) was by many standards the most important figure in the development of modern science. Many would credit him and Einstein with being the most original thinkers in that development.

56

Newton’s Synthesis

- Newton demonstrated that the motion of objects on the Earth could be described by three new Laws of Motion and that, if gravitational force were postulated to exist between all objects having mass in the Universe, Kepler's laws were special cases of his laws.

57

Newton’s First Law of Motion

I. An object in motion tends to stay in motion and an object at rest tends to stay at rest, unless the object is acted upon by an outside force.

58

HTML Version of Newton's First Law of Motion

Newton’s Second Law of Motion

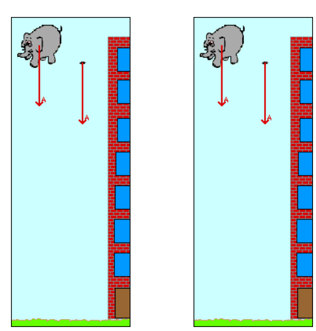
II. The acceleration of an object is directly proportional to the net force acting upon it and inversely proportional to its mass.

Mathematically, this means: $F = ma$

Where: F = net force
m = mass of the object
a = the acceleration of the object

59

Illustration of Newton’s Second Law

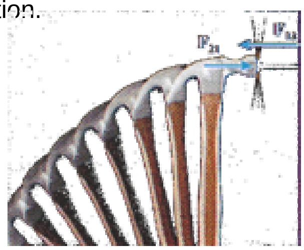


60

HTML Version of Newton’s Second Law of Motion

Newton's Third Law of Motion

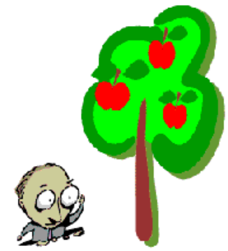
III. Every action has an equal and opposite reaction.



61

The Universal Law of Gravitation

- There is a popular story that Newton was sitting under an apple tree, an apple fell on his head, and he suddenly thought of the Universal Law of Gravitation. This is probably not true in its details, but the story almost certainly contains elements of truth.



HTML Version of Newton's Apple

62

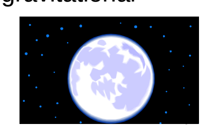
What Really Happened?

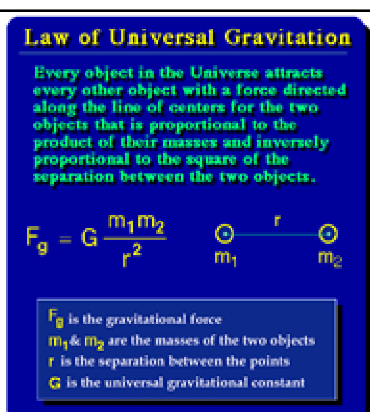
- Probably the more correct version of the story is that Newton, upon observing an apple fall from a tree, began to think along the following lines: The apple is accelerated as it moves from the tree toward the ground. There must be a force that acts on the apple to cause this acceleration. Let's call the force gravity" and the associated acceleration the "acceleration due to gravity".

63

Newton's Excellent Idea

- Now came Newton's truly brilliant insight: if the force of gravity reaches to the top of the highest tree, might it not reach even further to the orbit of the Moon. Then, the orbit of the Moon about the Earth could be a consequence of the gravitational force.

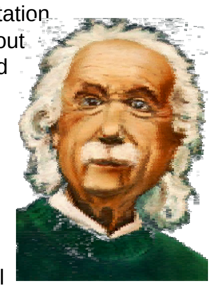




65

Albert Einstein

- Newton's theory of gravitation was soon accepted without question, and it remained unquestioned until the beginning of this century when Albert Einstein (1879-1955) shook the foundations of physics with the introduction of his Special Theory of Relativity (1905) General Theory of Relativity (1915).



66

Special Theory of Relativity

- Einstein's *Special Theory of Relativity*, challenged common sense perceptions and interpretations of space and time. The theory states that relative to the observer, both space and time are altered near the speed of light – distances appear to stretch and clocks tick more slowly.

67

General Theory of Relativity

- His *General Theory of Relativity* challenged Newtonian assumptions about a "clockwork universe" and the nature of gravity. To Einstein, gravity is a local warp in the fabric of space-time, rather than a distant force.*

*This new theory of gravitation paved the way for scientists to first conceptualize, then study and simulate the behavior of black holes.

68

Paradigm-Shifting Physics

- With two important ideas, Einstein developed his paradigm-shifting physics:
  - The speed of light is a constant – it's the same for all observers, regardless of how they are moving relative to the light source.
  - All observers moving at constant speed should observe the same laws of physics.

69

New Frame of Reference

- Putting these two ideas together, Einstein showed that the only way this can happen is if time intervals and/or lengths change according to the speed of the system relative to the observer's frame of reference. This flies against our everyday experience but has since been demonstrated to hold in a number of very solid experiments. For example, scientists have shown that an atomic clock traveling at high speed in a jet plane ticks more slowly than its stationary counterpart

70

Matter and Energy

- This led Einstein to the realization that matter and energy are interrelated and to the formula that expresses this relationship mathematically:

$E = mc^2$.

Where: E = energy
m = mass
c = the speed of light (a constant)

71

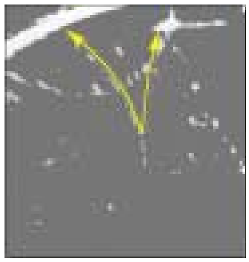
Einstein Explains the Equivalence of Energy and Matter

- It followed from the special theory of relativity that mass and energy are both but different manifestations of the same thing -- a somewhat unfamiliar conception for the average mind. Furthermore, the equation E is equal to m c-squared, in which energy is put equal to mass, multiplied by the square of the velocity of light, showed that very small amounts of mass may be converted into a very large amount of energy and vice versa. The mass and energy were in fact equivalent, according to the formula mentioned before. This was demonstrated by Cockcroft and Walton in 1932, experimentally.

72

Conversion of Energy into Mass

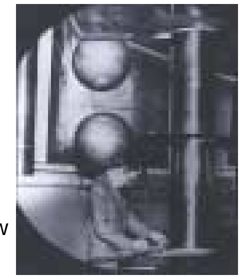
- This photograph shows the conversion of energy into mass and confirms Einstein's idea that a light-particle will yield up its quantum of energy all at once in a single burst.



73

Conversion of Mass into Energy

- The conversion of mass into pure energy is also possible. With their apparatus John Cockcroft and E.T.S. Walton broke apart an atom. The frag-ments had slightly less mass in total than the original atom, but they flew apart with great energy.



74

The Concept of Relativity

- Through the exchange of articles, ideas, and equations with other scientists, Einstein worked out a "general" theory that accounted for the influence of gravity on the motion of bodies, the shape of space, and the flow of time. Einstein wrote, "General relativity is beautiful and simple (to a physicist), but mathematically it's very complicated and subtle."

75

Einstein’s Continued Influence

- Einstein's theories continue to inspire exploration. Scientists find new ways to test and communicate abstract concepts and models. In the words of physicist John Wheeler, "matter tells space-time how to curve, and curved space tells matter how to move."

76

Sources

- Ptolemy
  http://zebu.uoregon.edu/~js/glossary/ptolemy.html
- The Ptolemaic System
  http://es.rice.edu/ES/humsoc/Galileo/Things/ptolemaic_system.html
- The Universe of Aristotle and Ptolemy
  http://csep10.phys.utk.edu/astr161/lect/retrograde/aristotle.html
- Cosmology from Ancient Greece to the Copernican Revolution
  http://www.scivis.com/AC/hist/cosmology.html
- Albert Einstein: Image and Impact
  http://www.aip.org/history/einstein/index.html

77