Measuring the Universe

A Brief History of Time & Distance from Summer Solstice to the Big Bang

Michael W. Masters

Outline

Part I

- Seasons and Calendars
- Greece Invents Astronomy
- Navigation and Timekeeping
- Measuring the Solar System

Part II

- The Expanding Universe

Origins of Astronomy

- Astronomy is the oldest natural science
  - Early cultures identified celestial events with spirits
- Over time, humans began to correlate events in the sky with phenomena on earth
  - Phases of the Moon and cycles of the Sun & stars
    - Stone Age cave paintings show Moon phases!
  - Related sky events to weather patterns, seasons and tides

- Neolithic humans began to grow crops (8000-5500 BC)
  - Agriculture made timing the seasons vital
  - Artifacts were built to fix the dates of the Vernal Equinox and the Summer Solstice

- Astronomy's originators include early Chinese, Babylonians, Greeks, Egyptians, Indians, and Mesoamericans

A 16,500 year old night sky map has been found on the walls of the famous Lascaux painted caves in central France. The map shows three bright stars known today as the Summer Triangle.

Source: http://ephemeris.com/history/prehistoric.html

Astronomy in Early History

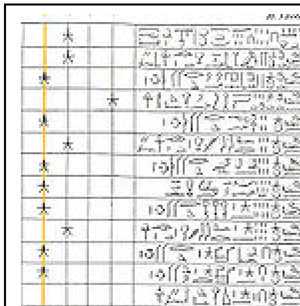
- Sky surveys were developed as long ago as 3000 BC
  - The Chinese & Babylonians and the Greek astronomer, Meton of Athens (632 BC), discovered that eclipses follow an 18.61-year cycle, now known as the *Metonic cycle*
  - First known written star catalog was developed by Gan De in China in 4th Century BC
  - Chinese were first to record a supernova, in 185 AD

Chinese star chart 940 AD

Babylonian tablet with eclipses 518 - 465 BC Mentions Xerxes' death

- Babylonian observations & methods were the basis for much of later Greek and Western astronomy
  - First to recognize that astronomical events are periodic and subject to mathematics
  - Surviving clay fragments contain ephemerides (tables of object positions over time)

http://www.cosmosfrontier.com/astronomy/the-sky/ancient-beliefs.html



Star clock, tomb of Rameses VI

- Egypt built astronomical observations into the pyramids
  - Pyramids were aligned towards the pole star
    - Tuban, in Draco, at the time due to precession
  - One theory says that the three pyramids on the Giza Plateau reflect the alignment of the stars in Orion's Belt
  - Great Temple of Amun-Re at Karnak was aligned to the rising of the midwinter Sun

Great Pyramids of Egypt

Wikipedia.com

http://www.nhn.ou.edu/~jeffery/astro/astlec/lec004.html

Astronomy in Early History

- Indian Astronomy dates to 1200 BC
  - Lagada documented lunar & solar calendar
  - Circa 500 AD, Aryabhata proposed earth's rotation & earth-centered solar system
  - First to suggest elliptical planetary orbits

Azophi's *Book of Fixed Stars* contained a thousand stars and described the Andromeda Galaxy and the Large Magellanic Cloud

- Mayans used Venus as well as Sun and Moon to create calendars

Persian bas-relief
On the day of an equinox, the power of a fighting bull (Earth) and a lion (Sun) are equal.

Mayan Pyramid at Chichen Itza
The descent of the snake, Kukulkan
Afternoon of spring equinox, a shadow moves down the side of the pyramid steps and ends at the snake head of Kukulkan at the bottom

- The Arabic world kept astronomy alive during the medieval era
  - Most of the names for stars 2nd magnitude & below were given by Arab astronomers
  - *Book of Fixed Stars* (964 AD) by Persian Abd al-Rahman al-Sufi (Azophi) described stars and nebulae!

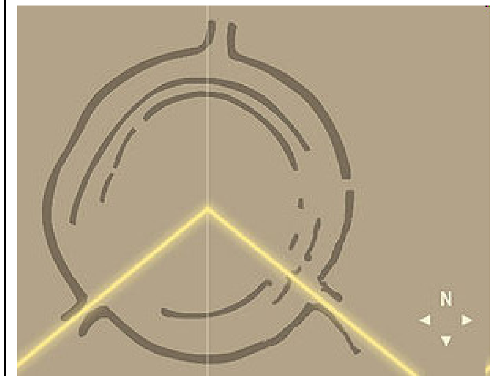
Wikipedia.com

Astronomy in Early Europe

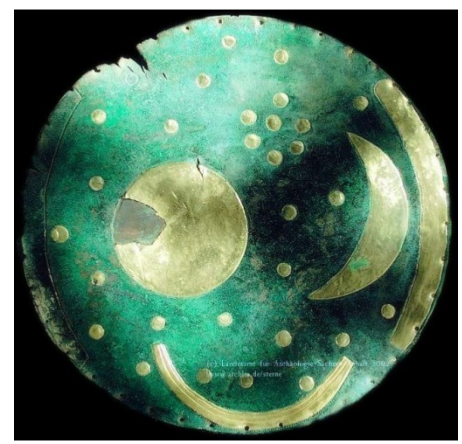
- Stonehenge, dating from ~2000 BC, is the best known of many similar structures in Britain
  - Avebury, Durrington Walls, Knowlton Circles, Maumbury Rings, Mayburgh Henge, Ring of Brodgar, Thornborough Henge, Great Circle at Stanton Drew
  - Purposes included marking seasons and predicting eclipses

Bad omen over Stonehenge

- Goseck Circle, also called the “German Stonehenge,” predates the English version (5000 BC)
  - One of 250 Neolithic structures in Germany marking winter solstice
  - Composed of concentric ditches with two Sun gates, the Gosic Circle is the earliest known sun observatory in the world
  - Nebra Sky Disc found nearby
- Sites in Britain and France show mathematics skills
  - Geometric relationships suggest knowledge of Pythagorean right triangle relationship
  - Stones trimmed in attempt to make Pi an integer!!



Goseck Circle, Germany
Yellow lines show the direction the Sun rises and sets at the winter solstice, vertical line shows astronomical meridian



Sky Disc of Nebra
3,600-year-old bronze artifact showing Sun, Moon & Pleiades
Nebra, Saxony-Anhalt, Germany

Ancient Calendars

- Ice-age hunters in Europe 20,000 years ago marked sticks and bones, possibly counting days between Moon phases
- 5000 years ago, Sumerians had a calendar that divided the year into 30 day months, days into 12 ”hours” and these periods into 30 parts. Later, Babylonians used a year of alternating 29 day and 30 day lunar months, giving a 354 day year

- Mayans (2600 BC-1500 AD) established 260 day & 365 day calendars, later use in Aztec calendar stones. They believed that creation occurred 3114 BC
- The Mayan calendar famously ends in 2012
  – **Apocalypse!**

- Early Egyptian calendars were based on lunar cycles. Around 3100 BC Egyptians observed that Sirius rose next to the Sun every 365 days, about the time of the annual flooding of the Nile, leading to creation of one of the earliest calendar years in history
  – Egyptians also established a “Year of Years” super-calendar of 1461 years, called the Sothic Cycle
  – Extra year substituted for quadrennial leap years

http://physics.nist.gov/GenInt/Time/ancient.html

Stonehenge as Astronomical Calculator

- Stonehenge is probably the most famous ancient astronomical calculator
  - Located on the Salisbury plain in the south of England, Stonehenge was built between 2000 BC and 1600 BC
  - Earlier timber and stone circles appear in the British Isles dating back to the late Neolithic period, about 3000 BC
- In modern times people knew of the Sun rising over the Heel Stone to mark the Summer Solstice

Summer Solstice at Stonehenge

- Gerald S. Hawkins' 1965 book, *Stonehenge Decoded,* suggested a great deal more in the way of astronomical calculations:
  - Stonehenge could calculate times in the solar year and times in the lunar month
  - With this knowledge, Britons could predict eclipses on a 56-year cycle, three times the 18.61-year *Metonic cycle* discovered by Chinese and Babylonians and documented by Greek astronomer Meton of Athens
  - Astronomer Fred Hoyle suggested that stones could be moved around in 56 Aubrey Holes. One of these stones on a certain Aubrey Hole would indicate an eclipse in that year

http://ephemeris.com/history/prehistoric.html

Outline

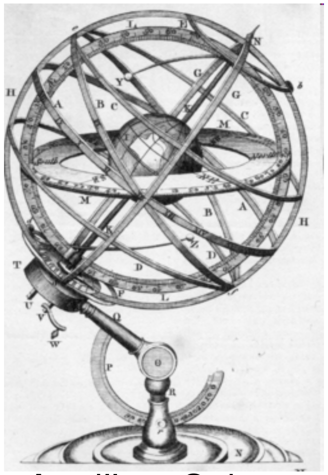
- Seasons and Calendars
- Greece Invents Astronomy
- Navigation and Timekeeping
- Measuring the Solar System
- The Expanding Universe

Hipparchus, Father of Scientific Astronomy

- Considered the greatest astronomer of antiquity
  - Made use of observations and methods of the Chaldeans from Babylonia
  - First to develop quantitative and accurate Sun & Moon motion models
  - Developed a reliable method to predict solar eclipses
- Discovered Earth's precession
- Developed trigonometry, made trigonometric tables, & solved spherical trigonometry problems
- Compiled first comprehensive Western star catalog
  - May have invented the astrolabe & armillary sphere for use in creating his star catalog

Hipparchus
c. 190 BC – c. 120 BC
Greek mathematician, astronomer, geographer, founder of trigonometry

It would be three centuries before Ptolemy's synthesis of astronomy would supersede the work of Hipparchus; Ptolemy's work depended heavily on Hipparchus

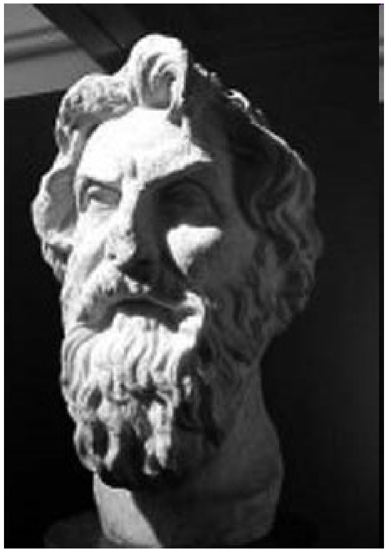


Armillary Sphere

Astrolabe, for locating Astronomical positions

Wikipedia.com

Aristarchus of Samos Estimated the Relative Distances to the Moon and the Sun



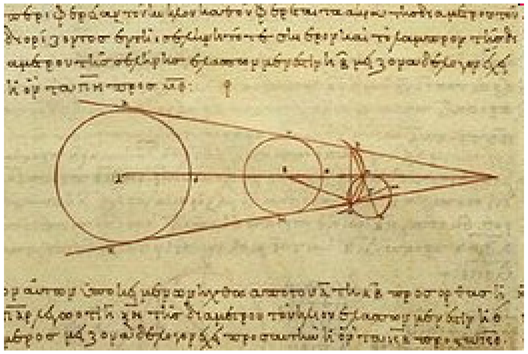
Aristarchus of Samos
310 – 230 BC
Greek astronomer and mathematician
First to propose a heliocentric model of the solar system

He figured out how to measure the **relative** distances from the Earth (E) to the Sun (S) and the Moon (M).

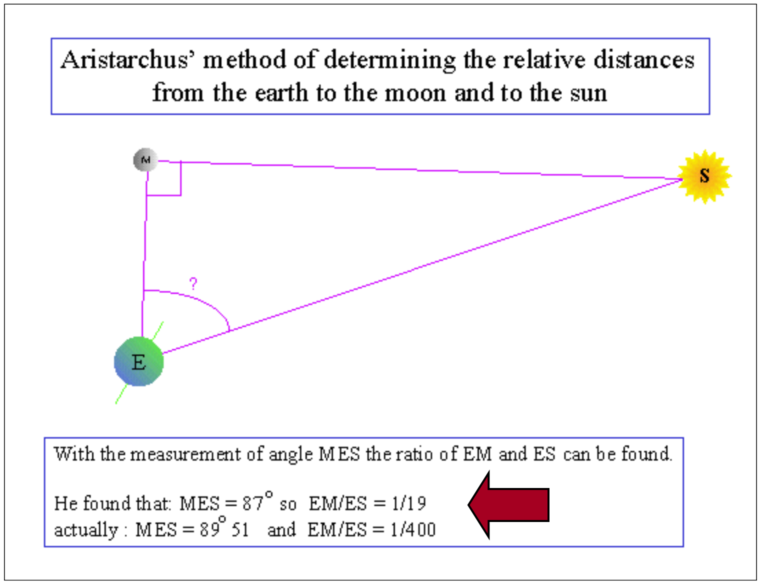
(Determining absolute distance ME would require knowing ES, and vice versa.)

When the Moon is exactly half full, the angle E-M-S must be exactly 90 degrees.

Therefore, the angle M-E-S when the Moon is half full will give the ratio of the Earth-Moon distance to the Earth-Sun distance.

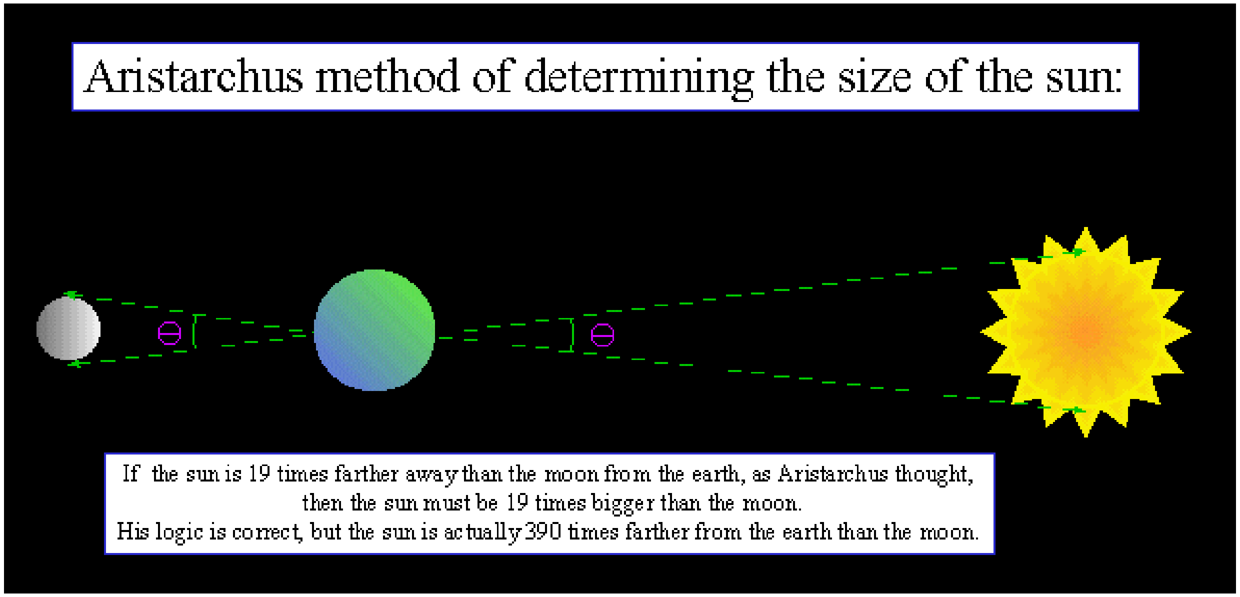


Aristarchus's 3rd century BC calculations on the relative sizes of the Sun, Earth & Moon, from a 10th century Greek copy



http://www.astro.cornell.edu/academics/courses/astro201/aristarchus.htm

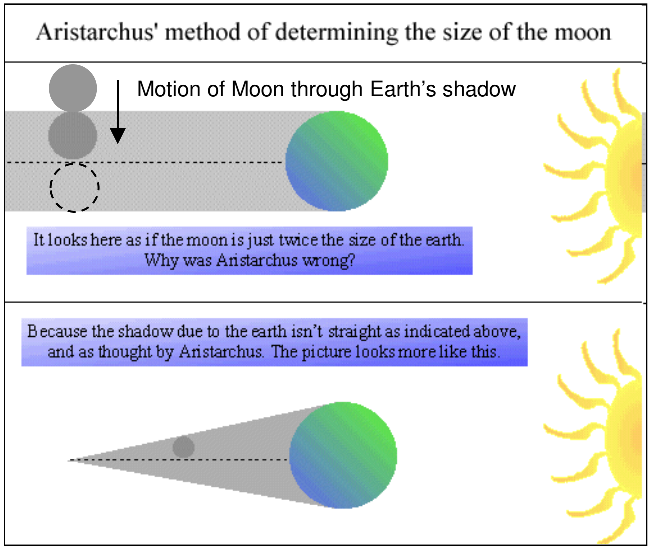
Aristarchus Estimated Relative Sizes of Moon & Sun



Because he deduced that the Sun was so much bigger than the moon, he concluded that the Earth must therefore revolve around the Sun.

Aristarchus also figured out how to measure the size of the Moon. During a lunar eclipse, he measured the duration of time between the moment when the edge of the Moon first entered the umbra and the moment when the Moon was first totally obscured. He also measured the duration of totality.

Because he found the two times to be the same, he concluded that the width of the Earth's shadow at the distance where the Moon crosses it must be twice the diameter of the Moon. The value is actually 4 times.

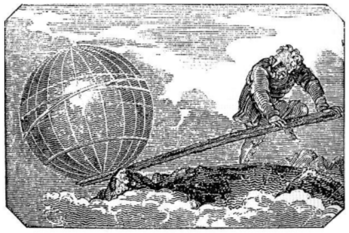


http://www.astro.cornell.edu/academics/courses/astro201/aristarchus.htm

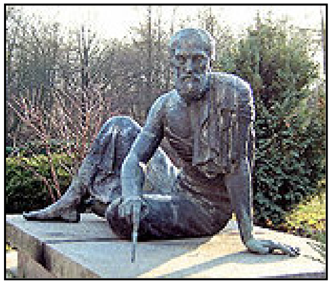
Archimedes Estimated the Size of the Universe!

> "... Aristarchus has brought out a book consisting of certain hypotheses. . .that the universe is many times greater than the [earth-centered] 'universe' just mentioned. His hypotheses are that the fixed stars and the Sun remain unmoved, that the Earth revolves about the Sun. . ."
>
> — Archimedes, *The Sand Reckoner*

- Archimedes of Syracuse set out to determine an upper bound to the number of grains of sand that would fit into the universe!
  - To do so, he had to estimate the size of the universe and invent a way to talk about extremely large numbers



- Large numbers were referenced to a "myriad", i.e. 10,000
  - Likewise, a "myriad myriads" was 10^8 and so on:, e.g. $\left((10^8)^{(10^8)}\right)^{(10^8)} = 10^{8 \cdot 10^{16}}$
  - In the process, Archimedes proved the law of exponents: $10^a 10^b = 10^{a+b}$
- To estimate the size of the universe, he used Aristarchus' heliocentric model, and made certain assumptions
  - Ratio of diameter of universe to diameter of Earth's orbit equals ratio of diameter of Earth's orbit to diameter of Earth
  - Perimeter of Earth < 300 myraid stadia (~300,000 miles)
  - Moon no larger than Earth and Sun < 30 times Earth
  - Angular diameter of Sun > 1/200 of right angle

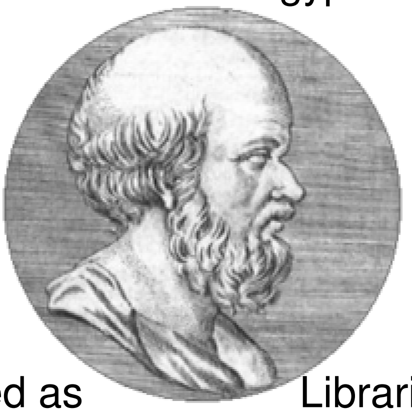


Archimedes of Syracuse
287 – 212 BC

- He then calculated that the diameter of the universe was no more than 10^{14} stadia (~2 light years) and could be filled with 10^{63} grains of sand!

Eratosthenes Measured the Earth's Circumference

Eratosthenes (Ἐρατοσθένης)
Born 276 BC Cyrene (Libya)
Died 195 BC Egypt



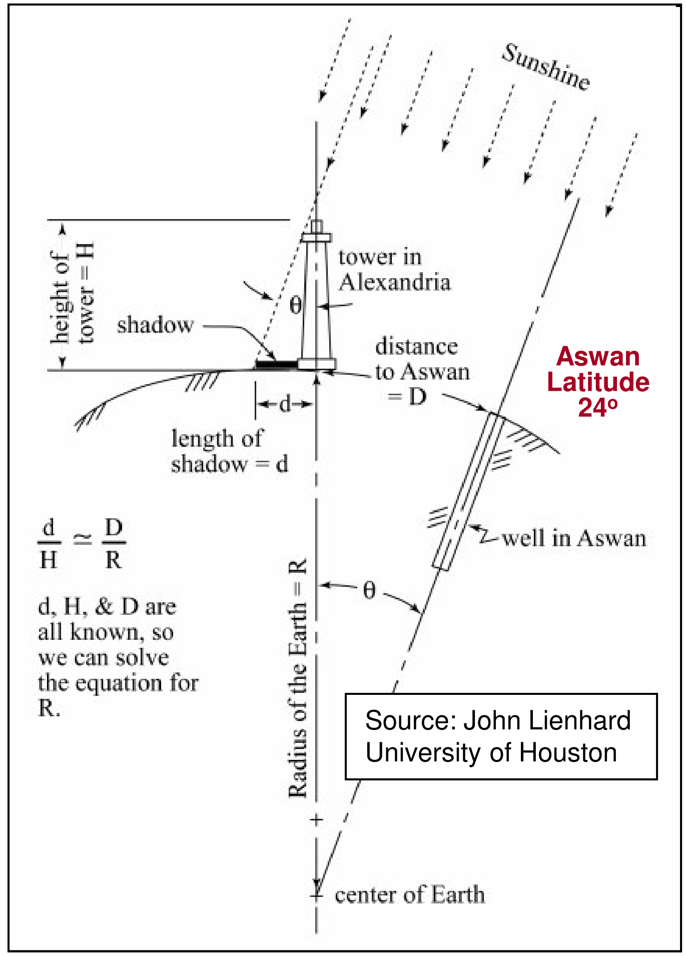
Served as Librarian of the Library of Alexandria, invented a system of latitude and longitude, **calculated the circumference of the Earth!**

Eratosthenes first calculated circumference of the earth.

He knew that on the summer solstice at noon in the city of Swenet (Syene in Greek, modern Aswan), the sun appeared directly overhead.

In Alexandria, he measured the sun to be 1/50 of a full circle (7°12') south of zenith at the same time.

Assuming Alexandria was due north of Syene he concluded that the distance from Alexandria to Syene must be 1/50 of the total circumference of the earth.



He estimated the distance between the cities at 5000 stadia (about 500 miles) using his time to travel from Syene to Alexandria by camel! He rounded the result to 700 stadia per degree, implying a circumference of 252,000 stadia.

The exact size of the stadion he used is uncertain. The Attic (Greek) stadium was about 185 m, which would imply a circumference of 46,620 km, 16.3% too large.

However, if Eratosthenes used the Egyptian stadium of about 157.5 m, his measurement turns out to be 39,690 km, an error of less than 1%!

Earth's tilt (currently 23.5°) varies between 22.1° and 24.5° over a period of 41,000 years.

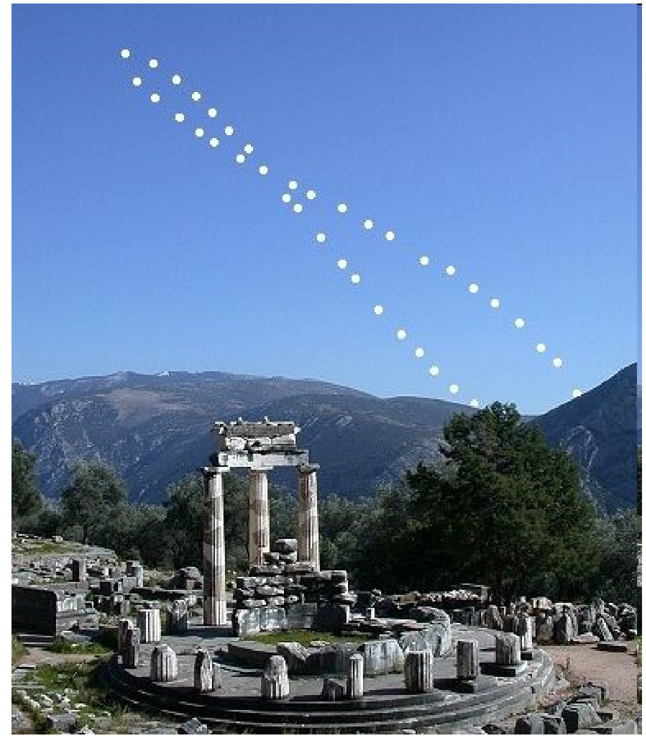
Wikipedia.com

The Antikythera Mechanism

- The Antikythera Mechanism accurately calculated positions of the Sun, Moon and planets. It included a calendar dial and a dial that predicted eclipses of the Sun and Moon
  - Oldest known complex scientific calculator
  - Found in 1902 by sponge divers in a shipwreck near Crete
  - Of Greek origin, estimated to date from ~100 BC
  - Composed of many gears, it is sometimes called the first analog computer

Antikythera Mechanism
Circa 150-100 BC

Reconstruction in the National Archaeological Museum, Athens



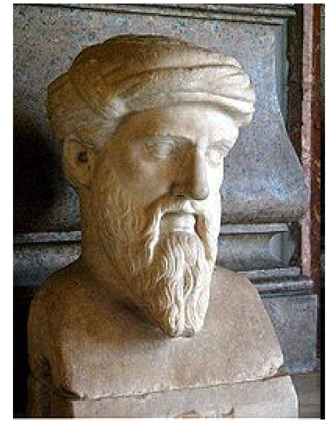
An ***analemma*** is the figure-8 loop formed when one marks the position of the Sun at the same time each day throughout the year.
http://antwrp.gsfc.nasa.gov/apod/ap030320.html

Michael Wright, Curator, London Science Museum
http://www.youtube.com/watch?v=4eUibFQKJql

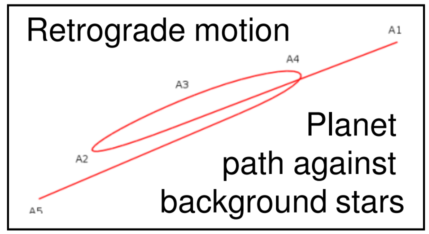
astro.umass.edu/~myun/teaching/a100/longlecture2.html
http://en.wikipedia.org/wiki/Antikythera_mechanism

The Ptolemaic System

- Pythagoras believed that planets were attached to crystalline spheres & moved in perfect circles
- Ptolemy refined previous ideas of astronomy
  - He believed that planets move in concentric circles around the Earth and in epicycles around their main orbits
    - First proposed by Apollonius of Perga, around 200 BC
    - Epicycles needed to explain planetary retrograde motion
  - Ptolemy used trigonometry to accurately measure the distance to the moon
  - Despite being wrong, his system predicted planetary motions with great accuracy

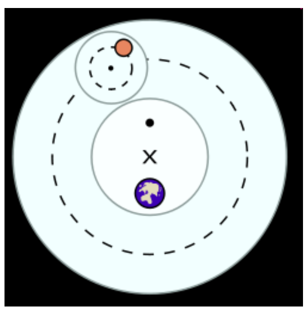


Pythagoras
570-495 BC
Greek
Mathematician

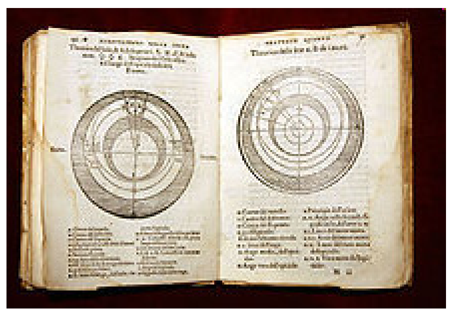


Ptolemy
90-168 AD
Egyptian
Astronomer

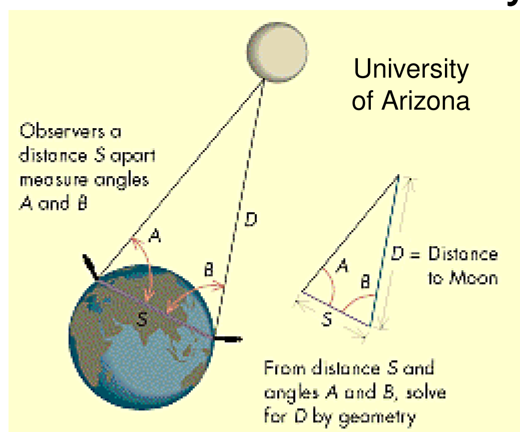
- The Ptolemaic system, described in Ptolemy's 13-volume treatise, the *Almagest,* became the astronomical authority for the next 1400 years



• = equant point
X = deferent center



Wikipedia.com



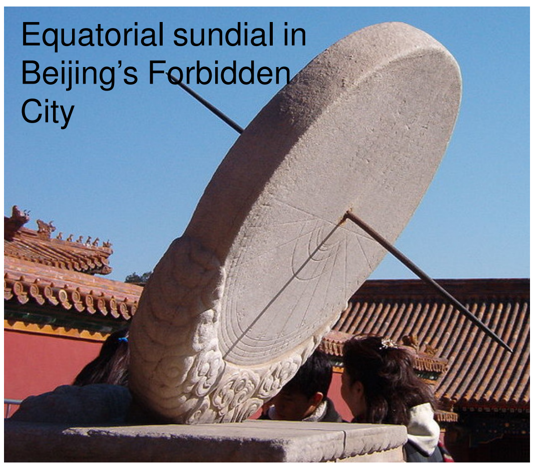
Outline

- Seasons and Calendars
- Greece Invents Astronomy
- Navigation and Timekeeping
- Measuring the Solar System
- The Expanding Universe

Early Clocks

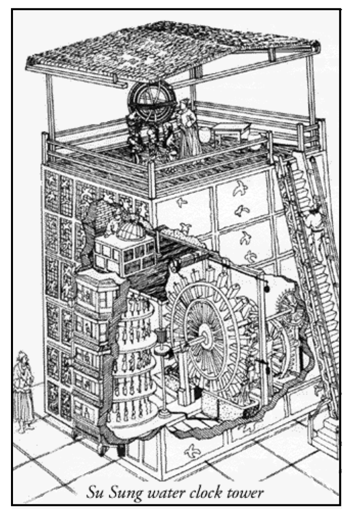
Early water clock

- The first clocks used the Sun, candles marked in increments, oil lamps with marked reservoirs, hourglasses, burning incense, etc.
  - Egyptians built obelisk sundials by 3500 BC
  - The Egyptian *merkhet* (600 BC) marked night-time hours by stars crossing the meridian
- Water clocks (*clepsydras*, “water thieves” in Greek) were marked stone vessels that dripped water from a small hole in the bottom
  - One of the oldest was found in the tomb of Pharaoh Amenhotep I
  - Another version was a metal bowl with a hole in the bottom; when placed in water the bowl filled and sank
  - These water clocks were still used in 20th century North Africa

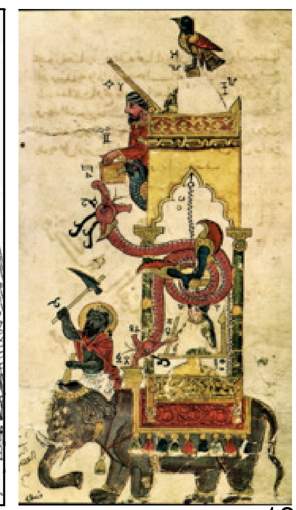


Equatorial sundial in Beijing’s Forbidden City

- Between 100 BC and 500 AD, Greek & Roman astronomers developed designs to regulate pressure for more constant flow of water
- Andronikos built the Tower of the Winds in Athens in the first century BC, showing seasons, dates & astronomical events
- Su Sung of China built one of the most elaborate water clocks in 1088 AD; over 30 feet tall, it possessed a bronze armillary sphere and a rotating celestial globe
- In 13th Century Byzantium, al-Jazari built two remarkable water clocks, his Castle Clock and his Elephant Clock
- The rate of flow of water is difficult to control; thus water clocks were never very accurate



Su Sung water clock tower

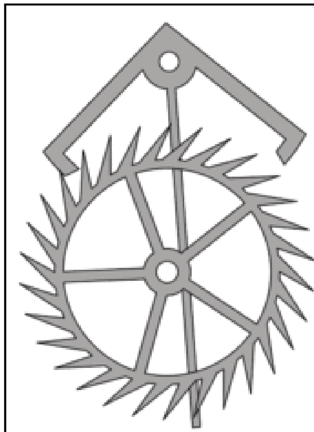


Wikipedia.com

Mechanical Clocks

Famous clock

- Key to development of non-water powered clocks was the invention of the escapement mechanism
  - Su Song's water clock had an escapement mechanism but still relied on water for power
  - A clock made in Iran (1300s) used mercury, but the principle was identical to water clocks



Deadbeat escapement used in pendulum clocks

- Mechanical clocks were invented in 13th century Europe
  - Based on oscillatory processes, more accurate than water flow
  - Controlled release of power from a falling weight by an escapement mechanism marked the beginning of true mechanical clocks
  - Spring driven clocks appeared during the 1400s
- Galileo suggested use of a swinging weight to regulate clock operation
  - Invention of the pendulum clock is usually attributed to Christiaan Huygens, who worked out the mathematical relationship between pendulum length and time

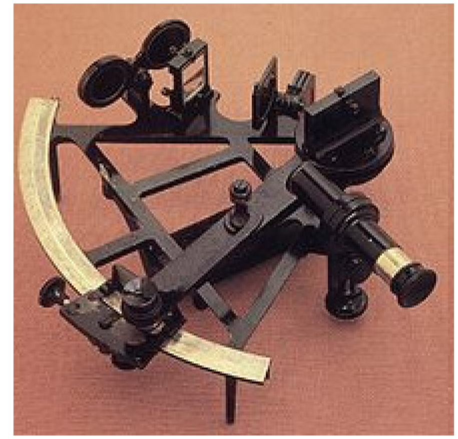
Anchor and escape wheel

- Need for accurate timekeeping to determine longitude during sea voyages drove clock development
  - Galileo suggested a celestial event as time reference

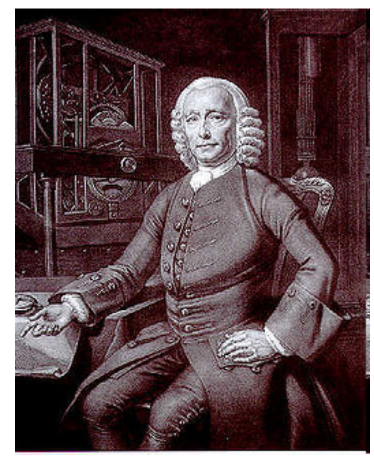
physics.nist.gov/GenInt/Time/revol.html
Wikipedia.com

John Harrison and the Marine Chronometer

- Navigation at sea required knowledge of latitude & longitude
  - Mariners calculated latitude in the Northern Hemisphere by sighting Polaris with a sextant. Generally, the height of Polaris above the horizon is the observer's latitude.
  - For most of history, mariners struggled to determine precise longitude. Longitude can be calculated if the precise time of a sighting is known.



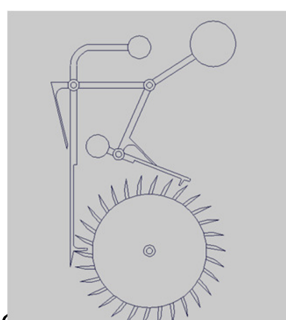
- English clockmaker John Harrison solved the problem with invention of the marine chronometer
  - Parliament offered £20,000 ($4.7M) for solution
  - Harrison approached Astronomer Royal Edmond Halley with initial design concept in 1730
  - Succeeded on fifth try, in 1773, despite personality based opposition from within the Board of Longitude
  - His H5 model won the cash award, with a little help from King George III and Parliament!
    - Board of Longitude never formally recognized Harrison!

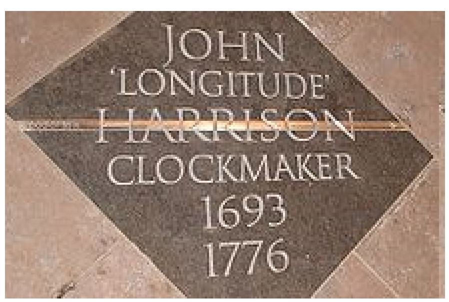


John Harrison
24 Mar 1693 – 24 Mar 1776
English Clockmaker
Invented Marine Chronometer
accurate to 1/3 sec/day

http://www.amazon.com/Longitude-Jonathan-Coy/dp/B00004U2K1/ref=sr_1_1?ie=UTF8&s=dvd&qid=1278599547&sr=1-1

Grasshopper escapement



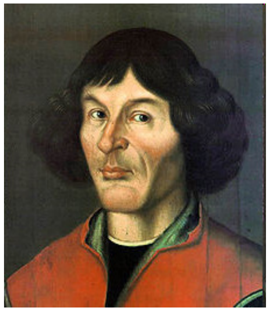


Wikipedia.com

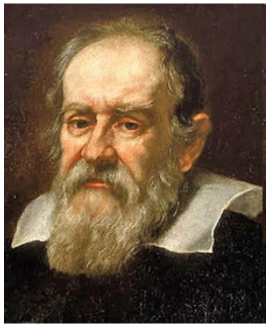
Outline

- Seasons and Calendars
- Greece Invents Astronomy
- Navigation and Timekeeping
- Measuring the Solar System
- The Expanding Universe

Birth of Modern Astronomy

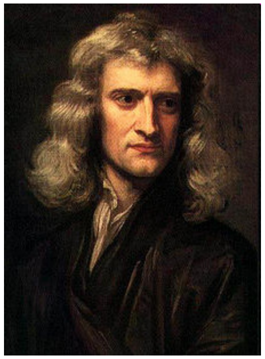


- Nicolaus Copernicus published *On the Revolutions of the Celestial Spheres* in 1543, just before his death
  - Heliocentric model marked the beginning of modern astronomy



- Galileo Galilei confirmed Copernicus with his 1610 treatise “Starry Messenger” detailing his telescope observations
  - First stated the principle of relativity (invariance of physical laws)
  - Stephen Hawking: “Galileo, perhaps more than any other single person, was responsible for the birth of modern science”

- Johannes Kepler developed the laws of planetary motion, published in *Astronomia nova (A New Astronomy),* 1609, and *Epitome of Copernican Astronomy, 1617-1621*
  - His work laid the foundation for Newton’s theory of gravity and the development of calculus
  - He used orbital mechanics to calculate the relative distances of the planets, later enabling absolute distances to be found



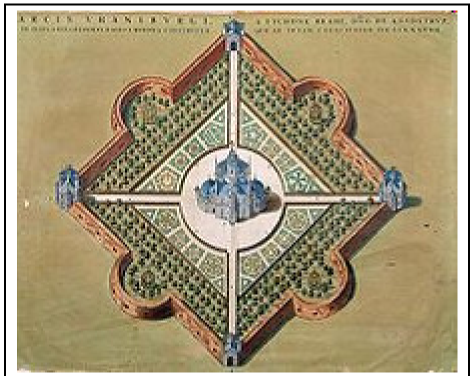
- Isaac Newton published *Philosophiae Naturalis Principia Mathematica* in 1687, defining a theory of universal gravity
  - Laws of motion, spectrum, telescope, calculus, other math. . .
  - Considered to be not only one of the greatest scientists, but one of the most influential figures in human history

Wikipedia.com

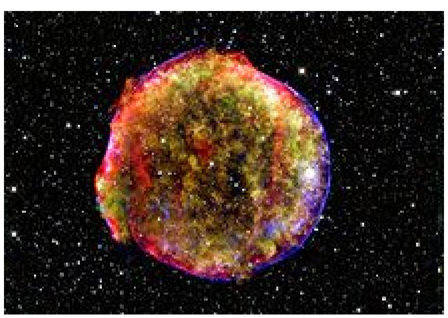
Tycho Brahe

Tycho Brahe
(1546–1601)
Danish Astronomer

- Brahe was a Danish nobleman known for accurate and comprehensive astronomical and planetary observations
  - Granted an estate on the island of Hven and funding for Uraniborg, an astronomical research institute
  - Following a disagreement with the Danish king, he moved to Prague in 1599, where he became imperial astronomer

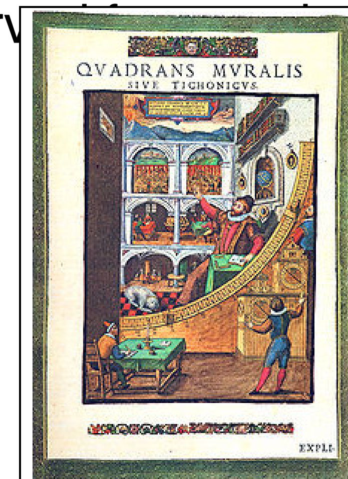


Uraniborg



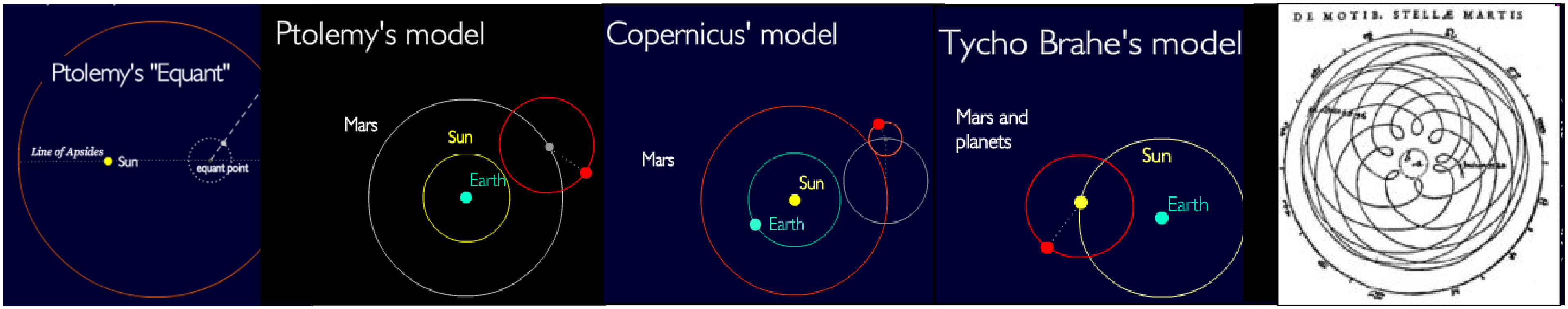
SN 1572

- Achieved measurement accuracy of 1-2 arcminutes
  - First to systematically correct for atmospheric refraction
  - Assisted by Johannes Kepler, his data became the observational basis for Kepler's laws of planetary motion
- Discovered supernova SN 1572, observ
  - No parallax against background stars meant that it lay beyond solar system
  - Ended forever the Aristotelian view of stars as fixed and immutable
- Oddities of Brahe's life
  - Believed in a modified Ptolemaic view & astrology; made herbal medicines
  - Lost his nose in a duel as a youth; died of bladder ailment following banquet

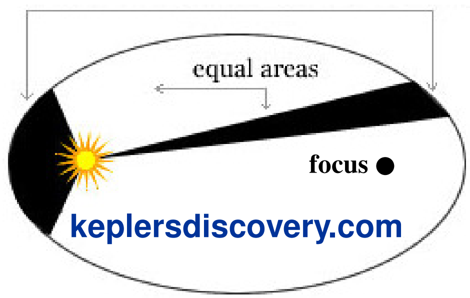


Mural Quadrant

Johannes Kepler Solved Planetary Motion

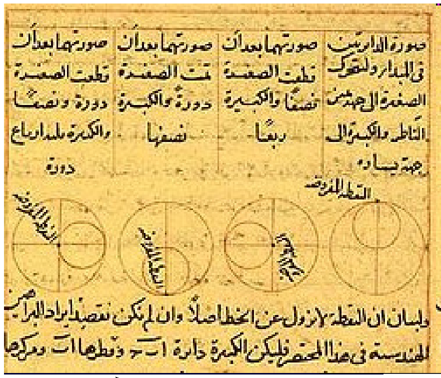


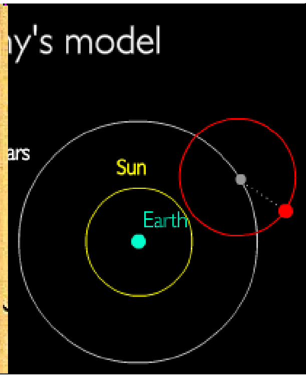
- Kepler initially wished to preserve the Ptolemaic model on religious grounds but could find no physical meaning for Ptolemy's "equant point"
  - How could an empty point, a mathematical abstraction, control planetary motion?
  - No one had ever thought to plot the motion of planets implied by Ptolemy's theory
- Kepler's derivation of the laws of planetary motion hinged on a discrepancy of 8 arc minutes in observations of the location of Mars
  - Brahe's observations, accurate to 1-2 arc minutes, were crucial
  - Planetary orbits are ellipses with the Sun at one of the two foci
  - A line from planet to Sun sweeps out equal areas in equal times
  - The square of the orbital period of a planet is directly proportional to the cube of the semi-major axis of its orbit

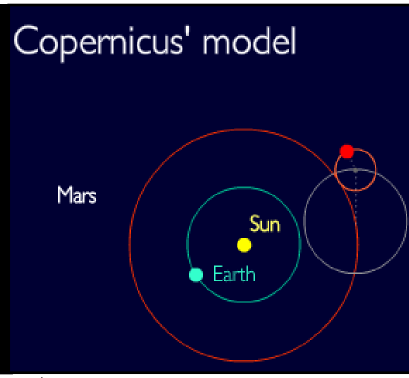


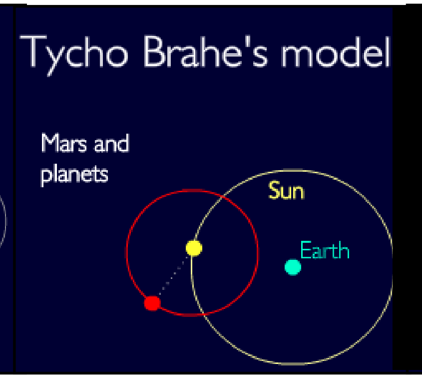
  - With these laws, the *relative* distances of the planets were known
- Kepler's discoveries anticipated calculus and Newton's gravity
  - Needed mathematics describing motion that changed each instant
  - Saw that the Sun had a power that moved the planets and that weakened with distance

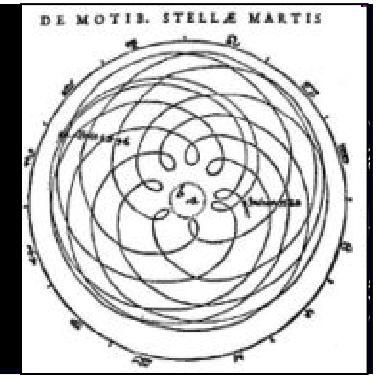
Johannes Kepler Solved Planetary Motion









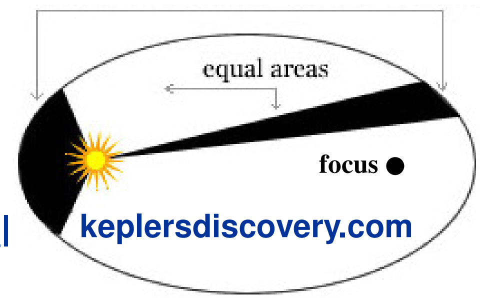


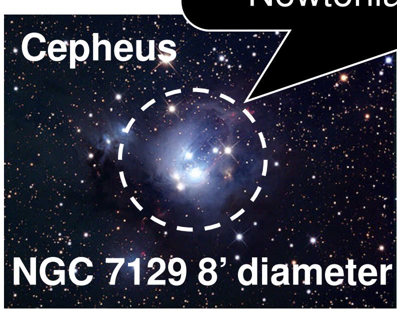
- K...ler initially wished to preser... the Ptolemaic model on religious grounds but ...t”
- ...ol planetary motion? ... by Ptolemy’s theory
- Kepler’s derivation of the laws of planetary motion hinged on a discrepancy of 8 arc minutes in observations of the location of Mars
  – Brahe’s observations, accurate to 1-2 arc minutes, were crucial
  – Planetary orbits are ellipses with the Sun at one of the two foci
  – ...out equal areas in equal times
  – ... a planet is directly proportional ... of its orbit
  – With these laws, the *relative* distances of the planets were known
- Kepler’s discoveries anticipated calculus and Newton’s gravity
  – Needed mathematics describing motion that changed each instant
  – Saw that the Sun had a power that moved the planets and that weakened with distance

Tusi-couple (circle within a circle) Proposed by Pesian astronomer Nasir al-Din in the 13th Century

By the 16th Century the slow accumulation of errors had led to a model with over 80 circles!

Field of view of a Nagler 2.5mm eyepiece used with a 16” f4.3 Newtonian reflector, at 800X!

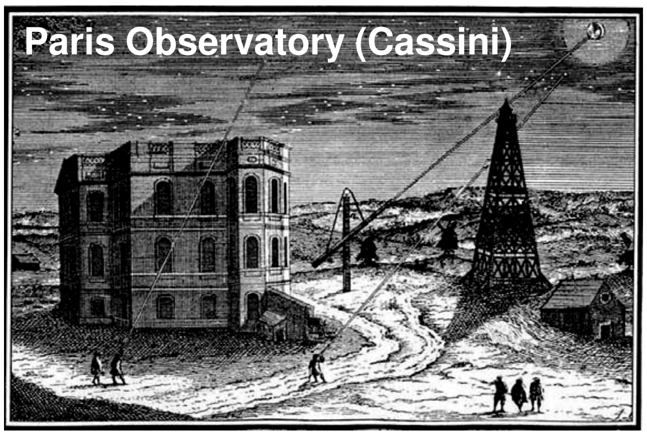




Jean Picard Measured the Earth's Radius

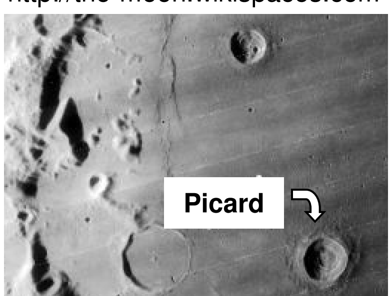
- Jean-Felix Picard was first to accurately measure the radius of the Earth (1669-70)
  - Used triangulation method defined by Willebrord Snellius
  - Measured one degree of latitude along the Paris meridian using triangulation along 13 triangles reaching from Paris to the clock tower of Sourdon, near Amiens
  - 6329 km vs modern value of 6357 km, .44% error

Jean-Felix Picard
(1620–1682)
French Astronomer



- Used screw micrometer, fitted a telescope with crosshairs
- Involved in other astronomical discoveries
  - Assisted Giovanni Cassini & Ole Rømer in measuring the speed of light
  - Observed a phenomenon called aberration of light while at Uraniborg with Ole Rømer
  - Newton used his observations in quantifying the constant of gravity
  - His discovery of mercurial phosphorescence led to Newton's studies of spectrometry
- Crater in Mare Crisium is named for Picard
  - Crater Snellius is named for Dutchman

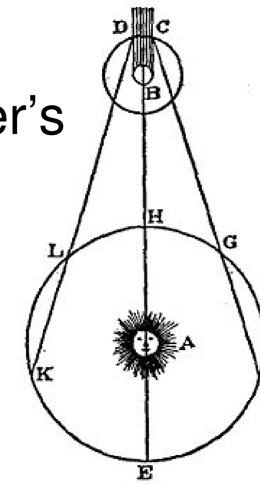
http://the-moon.wikispaces.com



Wikipedia.com

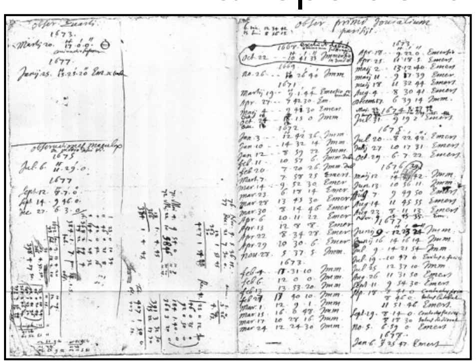
Willebrord Snellius
(1580–1626)
Dutch Astronomer

Ole Rømer and the Speed of Light



- In 1616, was the first Galileo to propose using eclipses of Jupiter's moon, Io, to determine time of day and thus longitude
- In 1671, Ole Rømer and Jean Picard at Uraniborg on Hven Isle and Giovanni Cassini in Paris timed the same eclipses of Io to determine longitude difference between the two cities (midday)
  - Their measurements was Δt=42 min 10 sec (modern 41:26)
  - (Cassini was first to find distance to a planet – Mars, via parallax)
- Rømer moved to Paris in 1672 to serve as Cassini's assistant

  - He observed that the time between eclipses got shorter as Earth approached Jupiter and longer as Earth moved away
  - Cassini had previously noticed discrepancies in eclipse times that he initially attributed to a finite speed of light
  - Cassini abandoned his theory but Rømer persisted and defined the mathematics for calculating the speed of light
- Rømer never published his theory because of Cassini's opposition
  - Rømer presented his work to the Royal Academy of Sciences in 1676, and a report of the talk was published in *Journal de scavans*



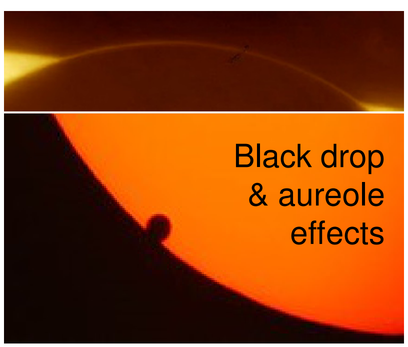
    - Rømer's estimate was about 26% low due to errors in Jupiter's orbital elements, later refined by Bradley & Foucault
  - Rømer wrote of his work to Christiaan Huygens, who is credited with first publication of a speed of light estimate
  - An Observatory of Paris plaque honors Rømer for what was the first measurement in history of a universal quantity

Wikipedia.com

Earth-Sun Distance

- Kepler's laws of planetary motion defined relative distances of planets to Sun
- Venus transit of Sun from two locations gives parallax for Venus
  - Relative Earth & Venus distances to Sun & Venus parallax gives solar parallax
  - Proposed by Scot James Gregory 1663
  - Published by Edmund Halley 1716
  - Expeditions in 1761 & 1769 (100+ years)
- Several other methods have been used
  - Aberration of light, first explained by Astronomer Royal James Bradley in 1725
  - Object appears at a different location due to observer motion & speed of light lag

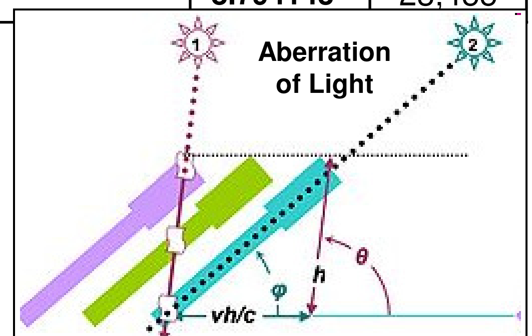
Scientist	Solar Parallax	Earth radii
Hipparchus (2nd century BC)	7’	490
Ptolemy (2nd century)	2′ 50″	1,210
Godefroy Wendelin (1635)	15″	14,000
Jeremiah Horrocks (1639)	15″	14,000
Christiaan Huygens (1659)	8.6″	24,000
Cassini & Richer (1672)	9½″	21,700
Jérôme Lalande (1771)	8.6″	24,000
Simon Newcomb (1895)	8.80″	23,440
Arthur Hinks (1909)	8.807″	23,420
H. Spencer Jones (1941)	8.790″	23,466
Modern	**8.794143″**	23,455



Transit of Venus across the face of the Sun

Date	Method	*A*/Gm	Uncertainty
1895	aberration	149.25	0.12
1941	parallax	149.674	0.016
1964	radar	149.5981	0.001
1976	telemetry	149.597 870	0.000 001
2009	telemetry	149.597 870 7	0.000 000 003

Since the Sun is losing mass, the value of A is constantly changing!



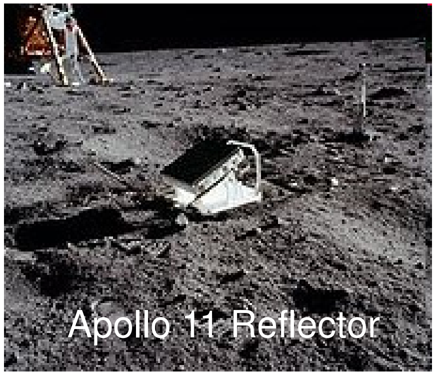
Light from location 1 will appear to be coming from location 2 for a moving telescope due to the finite speed of light, a phenomenon known as the aberration of light.

http://www.transitofvenus.nl
http://wikipedia.com

Apollo Lunar Laser Ranging Experiments

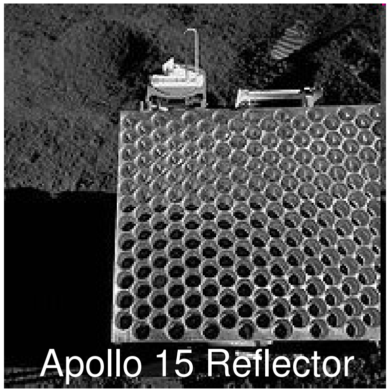
Laser Ranging Retroreflector experiments were deployed on *Apollo 11, 14, 15 and Lunakhod 2.* This consists of a set of corner reflector mirrors that always reflect a light beam back to its origin.

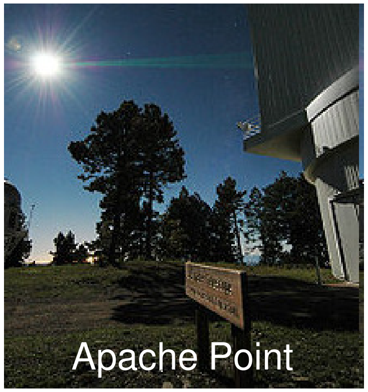
When illuminated by lasers the reflected laser beam provides a measurement of the round-trip distance between the Earth and the Moon. Measurements have been made by McDonald Observatory in Texas, Cote d’Azur in France, Apache Point in New Mexico and others.



- The average Earth-Moon distance is about 385,000 km, accurate to 3 cm
- The Moon is receding from the Earth at about 3.8 centimeters per year
- Variations in rotation imply the existence of a small core that was once liquid, with a radius of less than 350 kilometers
- The experiments put an upper limit on the change in Newton's gravitational constant *G* of < 1 part in 10^{11} since 1969
  - The experiments support the *Strong Equivalence Principle* (invariant gravity)
- Einstein's general theory of relativity predicts the moon's orbit to within the accuracy of the laser measurements.

NASA and Wikipedia.com





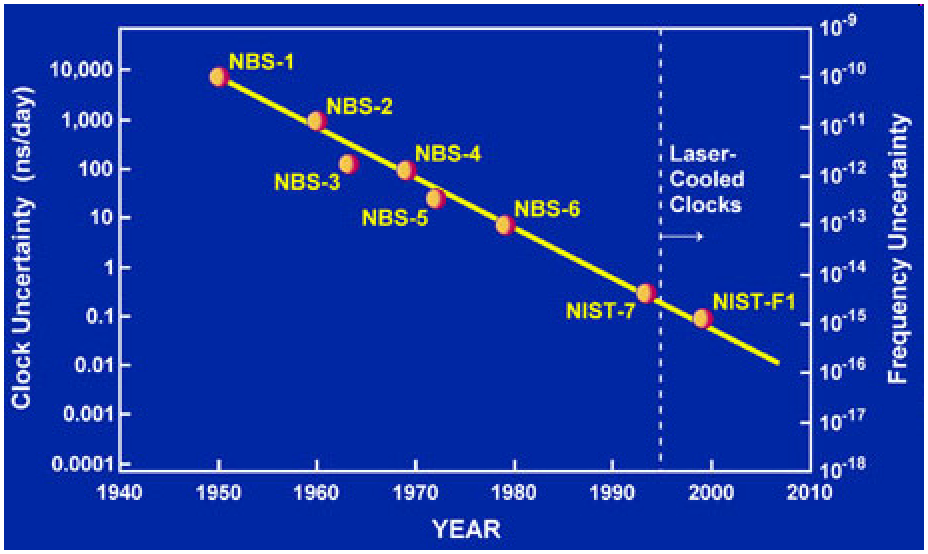
Atomic Clocks

An **atomic clock** uses a resonance frequency as its timekeeping element. Atomic clocks do not use radioactivity, but rather the precise microwave signals that electrons emit when they change energy levels.

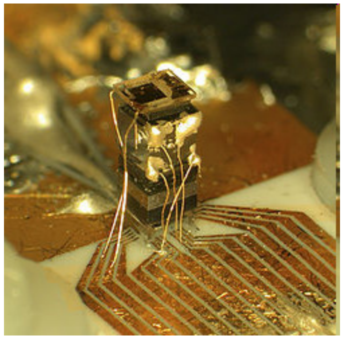
The core of an atomic clock is a microwave cavity containing ionized gas, a tunable microwave radio oscillator, and a detector & feedback loop that adjusts the oscillator to the absorption frequency of the atoms.

They are the most accurate time standards known, and are used as primary standards for international time and in navigation satellite systems such as GPS.

The idea of using atomic resonance to measure time was first suggested by Lord Kelvin in 1879!



NIST chip-scale atomic clock

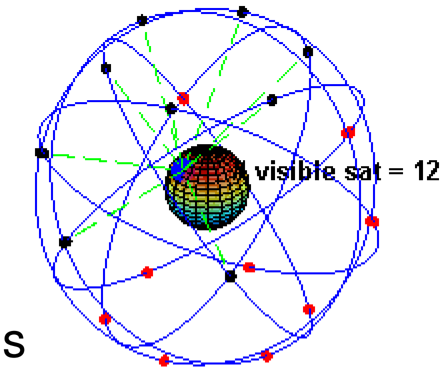


NIST quantum logic clock based on individual mercury and aluminium ions. These two clocks are the most accurate that have been constructed to date, with less than one second error in a billion years.

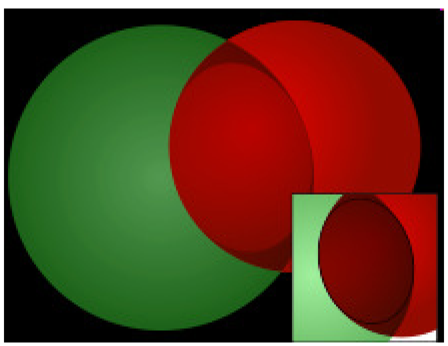
FOCS 1, a continuous cold cesium fountain atomic clock in Switzerland, started operating in 2004 with uncertainty of one second in 30 million years

The master U.S. Naval Observatory atomic clock, which provides the US time standard.

Global Positioning System



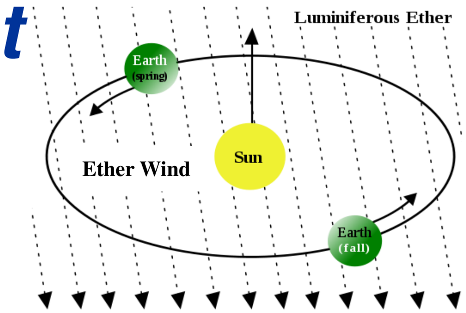
- GPS consists of three parts
  - Space segment of 24 to 32 satellites
  - Redundant control segment operated by USAF and a host of ground antennas and monitoring stations
  - User segment composed of secure and standard systems
    - Secure system: hundreds of thousands of military users
    - Standard system: millions of civil, commercial and scientific users
- Receiver uses four (or more) satellites to determine position
  - Receiver uses satellite signals to determine satellite location and time sent; receiver location is on a sphere centered on satellite
  - The intersection of two spheres defines a circle
  - The intersection of three spheres determines receiver location
  - Addition of a fourth satellite helps determine receiver clock error
- For GPS to work accurately, relativistic effects must be considered!



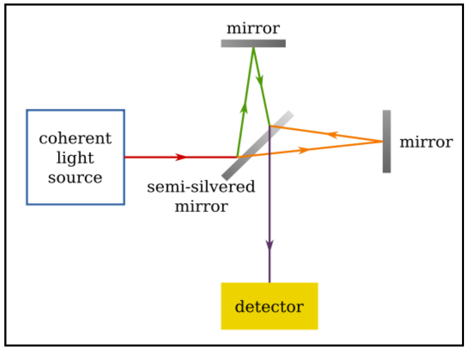
GPS Wide Area Augmentation System
Spec accuracy: 7m lateral & vertical
Accuracy in US: 1m lateral, 1.5m vertical

Wikipedia.com & Map-GPS-Info.com

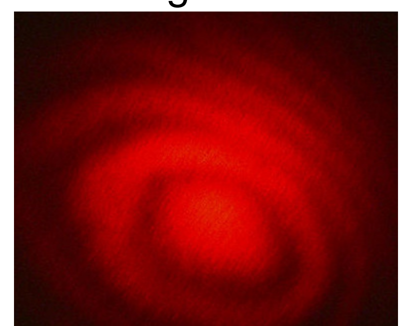
Michelson-Morley Experment



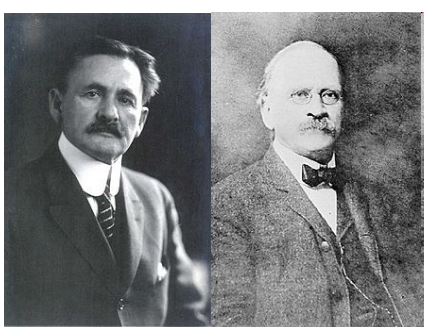
- Michelson-Morley experiment (1887) was the most famous failed experiment in the history of science!
  - Proved that there is no “luminiferous aether” through which light waves propagate



  - Paved way for both special relativity & quantum mechanics
    - Special relativity followed from Galileo’s principle of relativity, Michelson-Morely and Maxwell’s theory of electromagnetism
    - The quantum mechanics photon theory of light is incompatible with the idea of an ether propagation medium for light waves


Laser interference pattern

- Experiment consisted of sending light beams in different directions and measuring the difference in return times via interferometry


Albert Michelson & Edward Morley

Wikipedia.com

  - Ether wind would yield different travel times based on earth’s orbital velocity
  - Apparatus located in the basement of a stone building, on a huge block of marble floated in a pool of mercury!
    - Mercury allowed apparatus to be turned in any direction relative to the hypothetical “aether wind”
  - Experiments continued into the 20th century
    - e.g. Mount Wilson Observatory and using lasers and masers

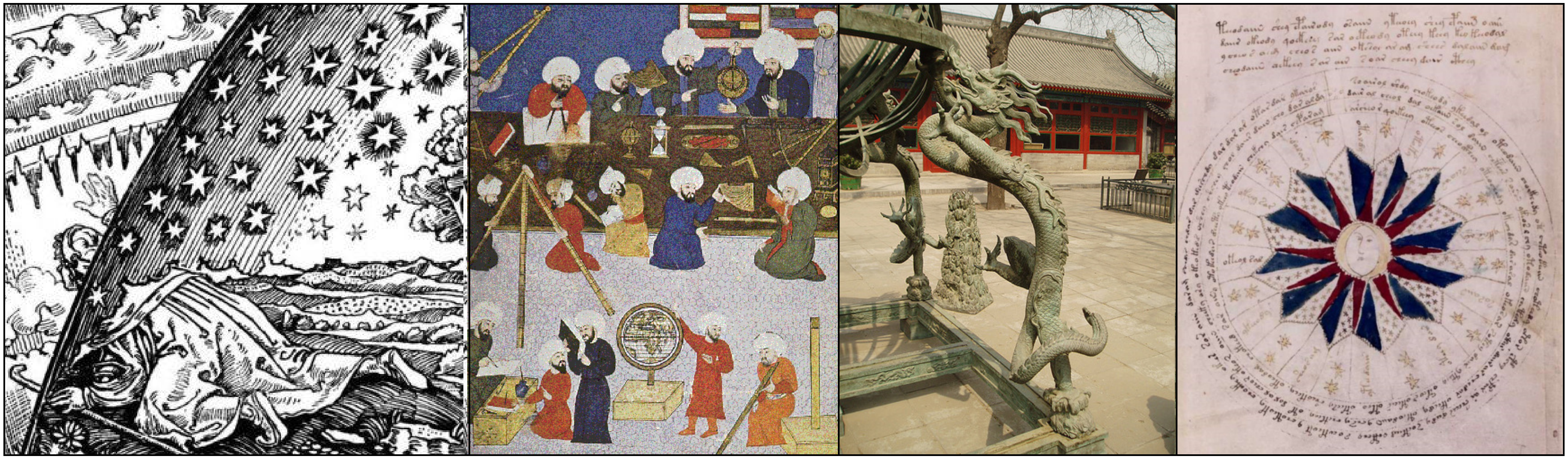
Outline

- Seasons and Calendars
- Greece Invents Astronomy
- Navigation and Timekeeping

End of Part I
- Measuring the Solar System

Part II
- The Expanding Universe

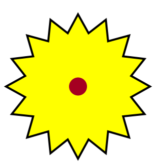
Questions & Answers



Fair Use Notice

In accord with Title 17 U.S.C. Sections 107-118, all copyrighted material herein is reproduced under fair use without profit or payment and is intended solely for the benefit of those receiving the information for non-profit research and educational purposes only.

[Reference: http://www.copyright.gov/fls/fl102.html, May 2009]



Never point a telescope at the sun
– unless it's a solar telescope, of course!!
. . .and don't look into the laser pointer either!!

Measuring the Universe

A Brief History of Time & Distance from Summer Solstice to the Big Bang

Michael W. Masters

Outline

- Seasons and Calendars
- Greece Invents Astronomy
- Navigation and Timekeeping
- Measuring the Solar System
- The Expanding Universe

Part II

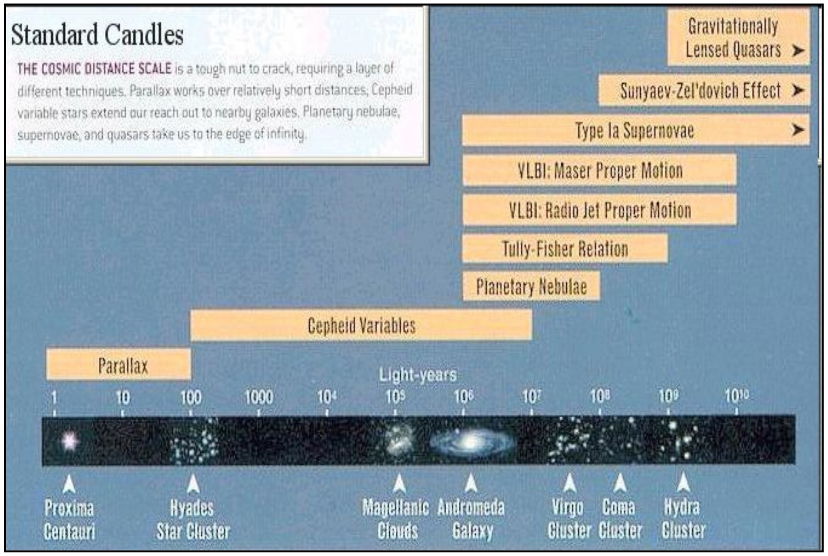
Summary of Part I – The Origins of Astronomy

- **Earliest sky observations dealt with religiosity, seasons & crops**
  - Cave artifacts in Europe date back to 20,000 years ago!
- **Babylonians, Chinese, Indians, Egyptians & Mesoamericans were among the first to make systematic observations of sky events**
  - Made calendars, discovered the Metonic cycle, that predicts eclipses
- **Hipparchus, Aristarchus, Archimedes, Eratosthenes, Ptolemy and others contributed to the founding of astronomy as a science of both theory and observation & measurement**
  - Invention of trigonometry and geometry served as enablers
- **The Copernican revolution ushered in an unprecedented flowering of scientific astronomy in the 1600s**
  - Brahe, Kepler, Galileo, Cassini, Rømer, Picard, Huygens, Newton. . .
  - Fall of the Aristotelian and Ptolemaic Earth-centered view of cosmos
  - Accurate timekeeping and navigation, advances in mathematics, Galileo's principle of relativity, development of Newton's theory of universal gravitation
- **Speed of light, radius of Earth, distances to Sun, Moon & planets**
  - Key methods were timings of eclipses of Io & transits of Venus and measures of parallax, requiring accurate timekeeping and angular measurements

Next, Part II – Modern Methods & the Expanding Universe

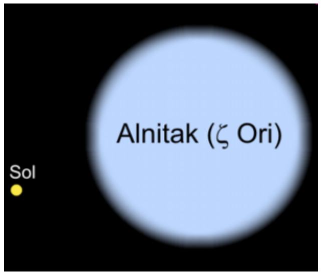
Measuring Distance in the Universe

- Finding distance by parallax is possible only for closest stars, so an overlapping chain of methods has been developed.
- At great enough distances, objects in the sky appear as point sources
  - Light from point sources diminish according to the inverse square law
- If a light source is known to have a constant luminosity, then its intensity can be used to calculate its distance.
- Many methods are used as **"standard candles"** to measure cosmic distance



http://universe-review.ca/R02-07-candle.htm

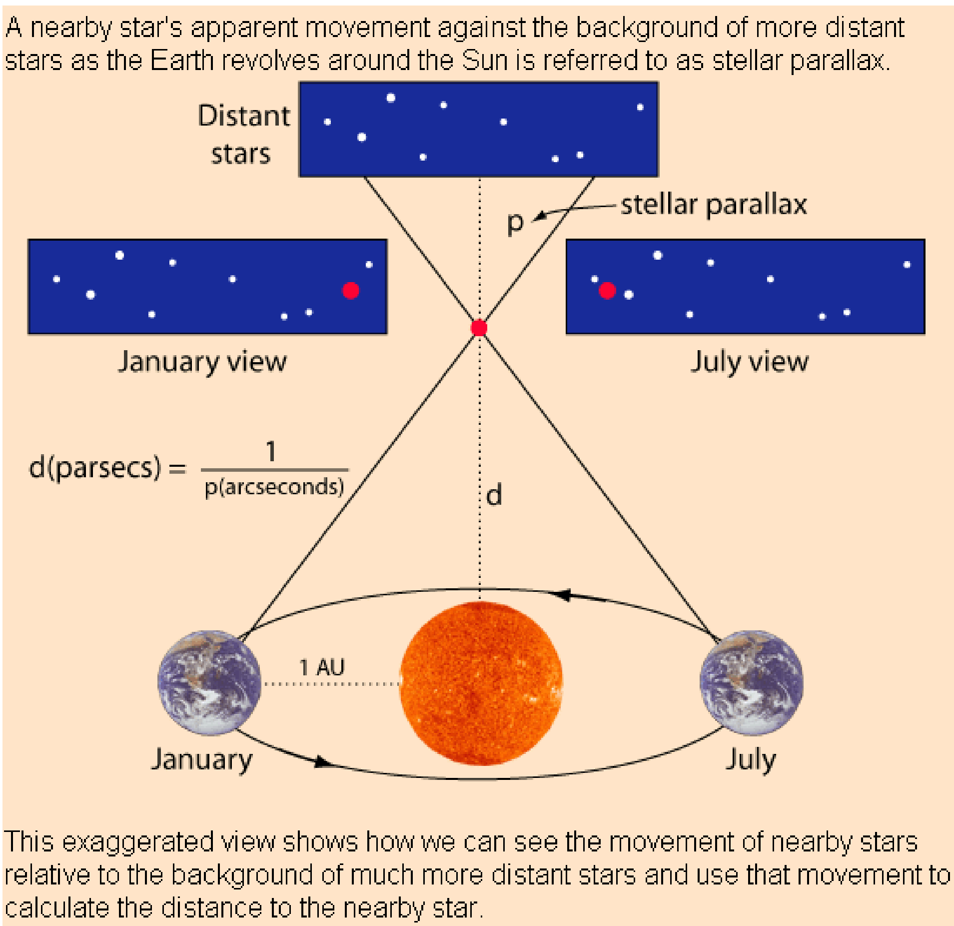
- Parallax / triangulation
- Signal reflection / telemetry
- Cepheid variables
- Planetary nebulae
- Most luminous supergiants
- Most luminous globular clusters
- Most luminous H II regions
- Type 1a supernovae
- Red shifts and Hubble's Law
- Gravitational lensing



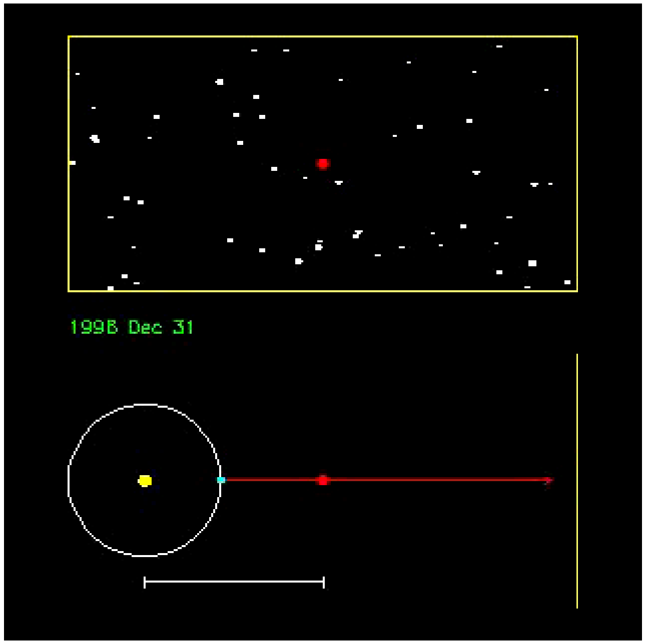
http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/distance.html#c1
http://en.wikipedia.org/wiki/Standard_candle
http://universe-review.ca/R02-07-candle.htm

Stellar Parallax as Measure of Distance

Prior to discovery of other means, distances to stars could only be determined by parallax, an angular measure based on the diameter of the Earth's orbit. First proposed by English mathematician Thomas Digges in 1573, German astronomer Friedrich Wilhelm Bessel measured the first star in 1838, 61 Cygni. Only about 2000 stars can be thus measured.



Source: Georgia State University



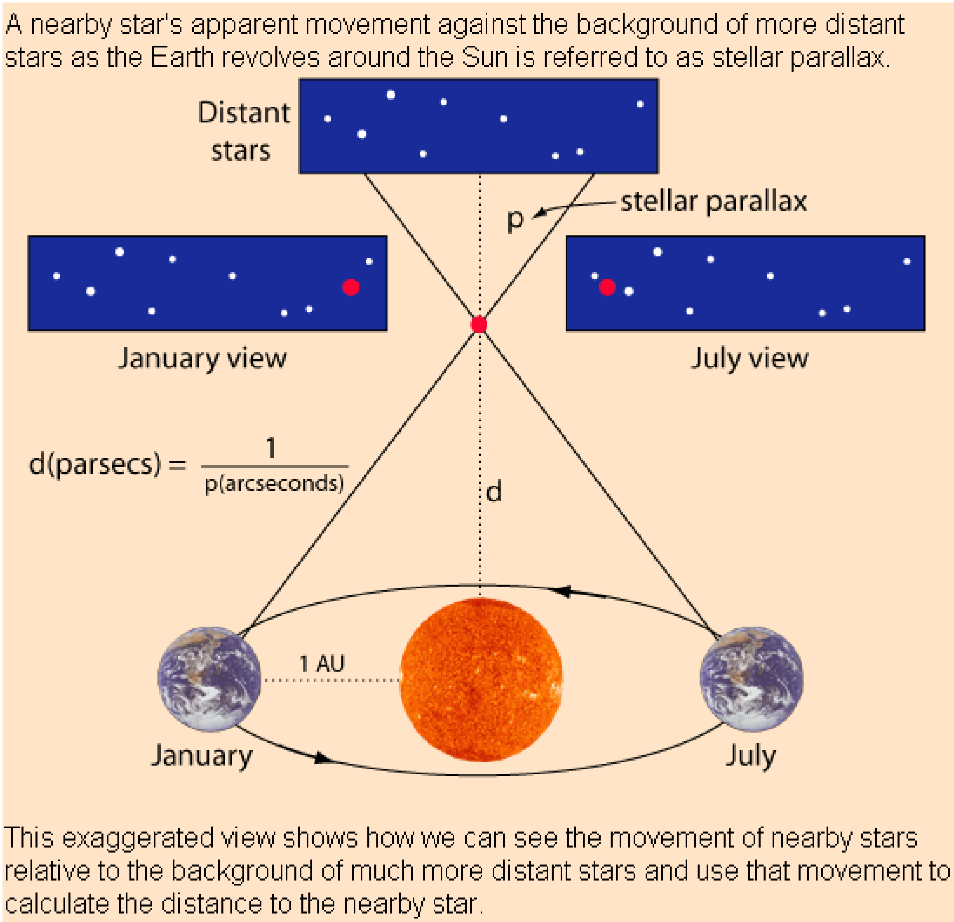
http://www.astronomy.ohio-state.edu/~pogge/Ast162/Movies/

***Parsec*: the distance from the Sun to an astronomical object which has a parallax angle of one arcsecond. A parsec is about 3.26 light years. The limit of earth-based parallax measurement is about 65 light years. The ESA's Hipparcos extended this to an accuracy of 0.001 arcsecond and approximately 120,000 stars.**

http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/para.html#c1

Stellar Parallax as Measure of Distance

Prior to discovery of other means, distances to stars could only be determined by parallax, an angular measure based on the diameter of the Earth's orbit. First proposed by English mathematician Thomas Digges in 1573, German astronomer Friedrich Wilhelm Bessel measured the first star in 1838, 61 Cygni. Only about 2000 stars can be thus measured.



Source: Georgia State University

<u>ESA's Hipparcos</u>

Launched in 1989, an important Hipparcos contribution was to make precise parallax measurements of 273 Cepheid variables, thereby providing an accurate calibration of the Cepheid period-luminosity relationship.

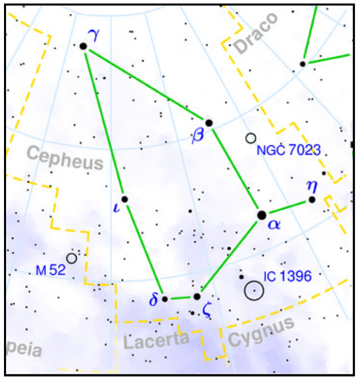
http://hyperphysics.phy-astr.gsu.edu/hbase/Solar/Hipparcos.html

<u>Parsec</u>: the distance from the Sun to an astronomical object which has a parallax angle of one arcsecond. A parsec is about 3.26 light years. The limit of earth-based parallax measurement is about 65 light years. ESA's Hipparcos satellite extended this to an accuracy of 0.001 arcsecond and approximately 120,000 stars.

http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/para.html#c1

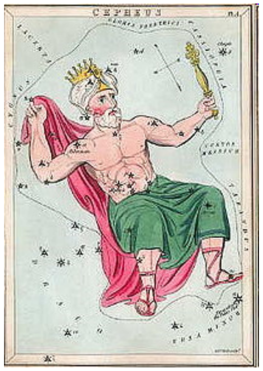
Pigott & Goodricke Discover Cepheid Variables

- Cepheids are pulsating variable stars
  - 5-20 solar masses, up to 30,000 times brighter than Sun
  - Period is typically a few days to months
  - Relation between luminosity and period is precise
  - **Allows Cepheids to serve as a "standard candle"**
  - HST has identified Cepheids out to 100 million light years

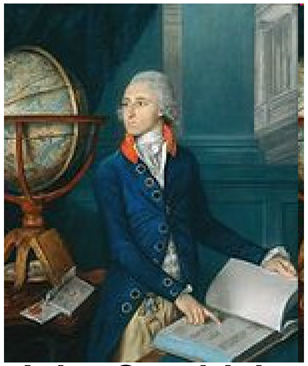


- Discoverer: English astronomer Edward Pigott (1753-1825)

  - Discovered M64 before Messier, in 1779
  - Observed variability of Eta Aquilae in 1784
  - Worked with young neighbor John Goodricke
  - Pigott & Goodricke were the first to measure brightness of stars that vary over time



- John Goodricke discovered variability of Delta Cephei
  - Presented a mechanism to account for the eclipsing binary variable Algol to Royal Society at age 18
  - Elected member of Royal Society in 1786
  - Goodricke was deaf due to childhood scarlet fever
  - Died at age 21of pneumonia



John Goodricke
1764 – 1786
English astronomer

Cepheid variables were named in honor of
John Goodricke's observations of Delta Cephei

Henrietta Swan Leavitt and the Cepheid Period-Luminosity Law

- Henrietta Leavitt began work at Harvard Observatory in 1893
  - Tasked by astronomer Edward Pickering to measure & catalog brightness of stars on photo plates of the Magellanic Clouds
  - An astute observer, on her own initiative she noticed that many were also variable
- She published her results in 1908 & 1912, noting that a few variables (Cepheids, or pulsating variables) showed a pattern: the brighter ones appeared to have longer periods
  - Her discovery became known as the "Period-Luminosity Law"
  - **This relationship provided a way to measure great astronomical distances**

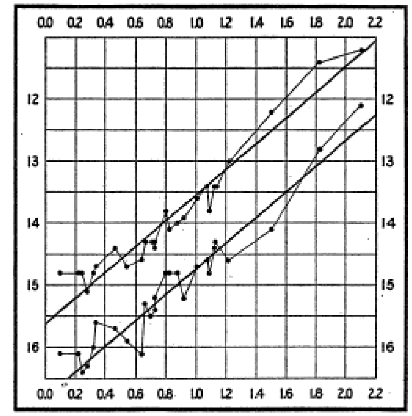


Fig. 2.

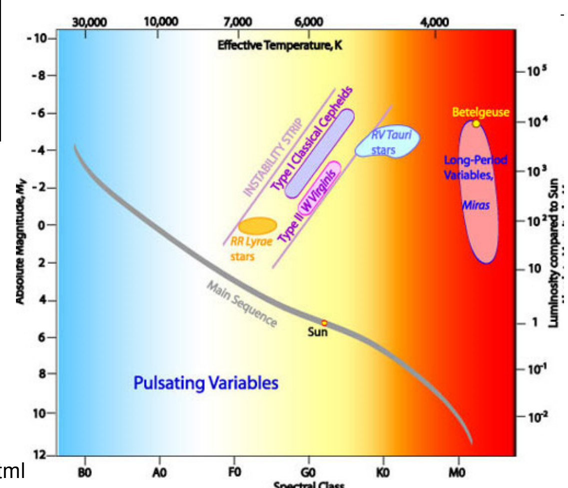
Henrietta Swan Leavitt
4 July 1868 – 12 Dec 1921
Educated Oberlin & Radcliffe
Employed Harvard University

Wikipedia.com

> **"Since the variables are probably at nearly the same distance from the Earth, their periods are apparently associated with their actual emission of light. . . It is to be hoped, also, that the parallaxes of some variables of this type may be measured."**
>
> **– March 1912**

In 1913 Ejnar Hertzsprung used statistical parallax methods to determine the distance to several Cepheids, providing a distance-luminosity calibration
(closest: Polaris at 430 LY)

http://outreach.atnf.csiro.au/education/senior/astrophysics/variable_pulsating.html



Standard Candles Out to 300 Million Light Years

Most Luminous Supergiants

The brightest supergiants in a given galaxy have about the same absolute magnitudes, about -8 for red supergiants and about -9 for blue supergiants. These two types of supergiants can be seen out to about 50 and 80 million light years respectively, compared to a maximum of about 20 million for Cepheid variables.

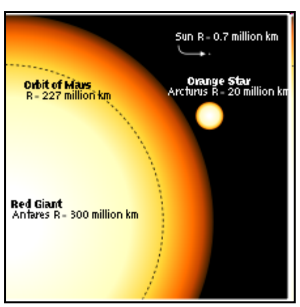
Most Luminous Globular Clusters

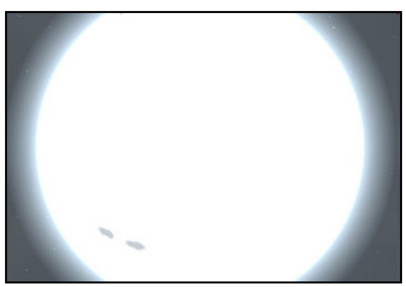
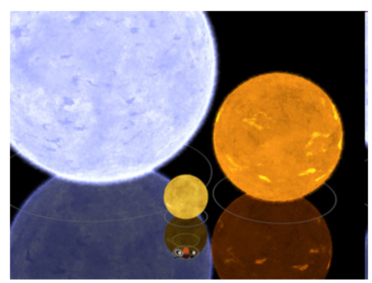
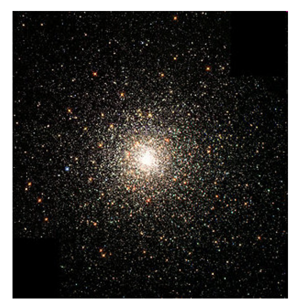
Beyond 80 million light years, even the brightest blue supergiants fade from view and one uses entire star clusters and nebulae for luminosity measurement. The brightest globular clusters have total luminosity of about magnitude -10 and can be seen out to 130 million light years.

Most Luminous H II Regions

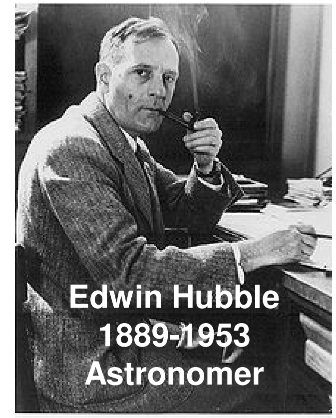
The brightest H II regions have absolute magnitudes of about -12 and can be detected out to about 300 million light years, compared to about 130 for the brightest globular clusters.

http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/dist2.html#c2

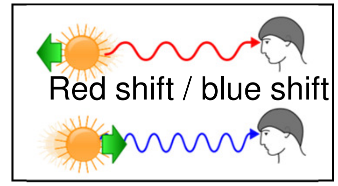


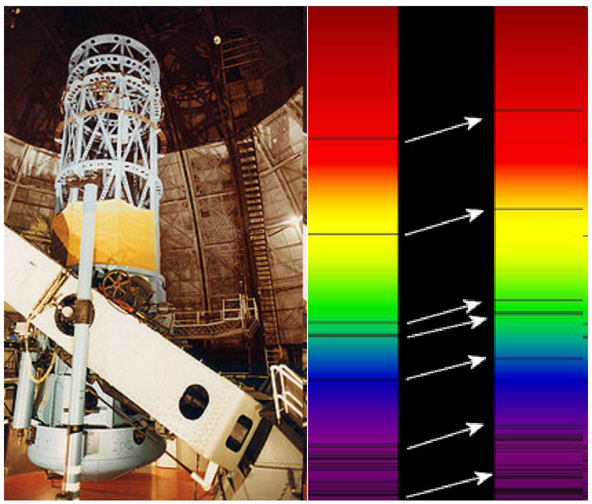




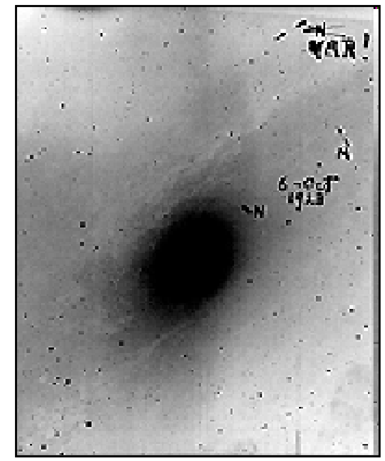

Cepheids as Standard Candle



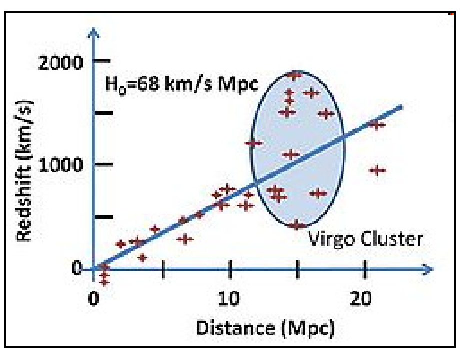
- In 1924 Edwin Hubble discovered Cepheid variables in the Andromeda galaxy. This settled the question of whether the Milky Way is merely one galaxy in a larger Universe
- In 1929 Hubble & Milton Humason formulated what is known as Hubble's law, establishing that the Universe is expanding







  - Vesto Slipher of Lowell Observatory was the first to publish galaxy redshift measurements, in 1913
  - Hubble used galaxy distances based on Leavitt's period-luminosity law for Cepheids (plus brightest stars) and Slipher and Humason's redshift data to correlate distance with redshift
  - They discovered a proportionality between galaxy distances and redshifts, and thus the speed at which they recede

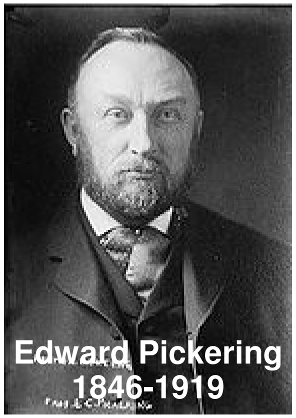


- Earlier, Harlow Shapley at Mt. Wilson had used Cepheids to estimate size & shape of the Milky Way, the Sun's location, & distance to globular clusters
- HST found the most distant Cepheid to date, in NGC 4603, at 108 M light-years

Postscript to the Cepheid Variable Story

- Both John Goodricke and Henrietta Swan Leavitt were deaf
  - Goodricke from childhood, Leavitt from young adulthood
- Goodricke never learned of his 1786 election as a Fellow of the Royal Society because he died of pneumonia four days afterward at age 21
  - Awarded the Copley Medal at 18 for Algol work
  - Asteroid 3116 Goodricke, Asteroid 10220 Pigott

- Leavitt was one of many women working as "Harvard computers" AKA "Pickering's Harem" who contributed to major astronomy advances
  - At the time women were not allowed to operate the telescopes
  - Yet Pickering hired ~ 40 women to assist, four of whom became successful astronomers (Williamina Fleming, Antonia Maury, Annie Jump Cannon)
  - Prior to her death in 1921, Leavitt became Head of Stellar Photometry



- Unaware of her death, Swedish mathematician Gosta Mittag-Leffler considered nominating Leavitt for the Nobel Prize
  - Leavitt's work was foundational to the discoveries of Edwin Hubble, who was said to also have believed she deserved the Nobel
  - Asteroid 5383 Leavitt and the Lunar crater Leavitt were named in her honor
  - "She had the happy faculty of appreciating all that was worthy and lovable in others, and was possessed of a nature so full of sunshine that, to her, all of life became beautiful and full of meaning."

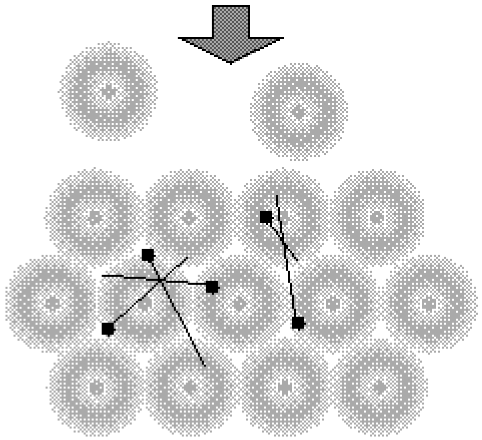
Wikipedia.com

Electron and Neutron Degeneracy Pressure

astronomynotes.com/evolutn/s11.htm# & Wikipedia.com

Mass < 1.4 solar masses

GRAVITY



White Dwarf

Electrons run out of room to move around. Electrons prevent further collapse. Protons & neutrons still free to move around.

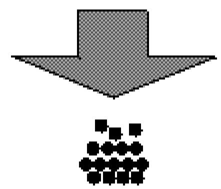
Stronger gravity => more compact.

Pauli Exclusion Principle

White Dwarf
~ Size of Earth

Mass > 1.4 solar masses
but mass < 3 solar masses

GRAVITY



Neutron Star

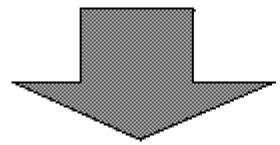
Electrons + protons combine to form neutrons. Neutrons run out of room to move around. Neutrons prevent further collapse. Much smaller!

Tolman–Oppenheimer–Volkoff limit

Neutron Star
~ 12 miles
diameter

Mass > 3 solar masses

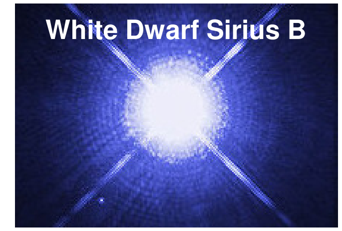
GRAVITY

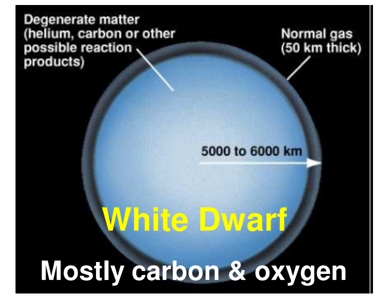


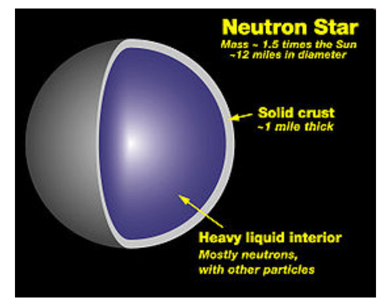
Black Hole

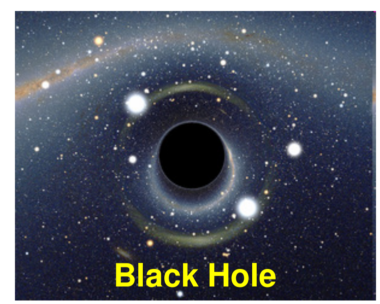
Gravity wins!
Nothing prevents collapse.

Schwarzchild
radius
(3 solar masses
~ 50 miles)

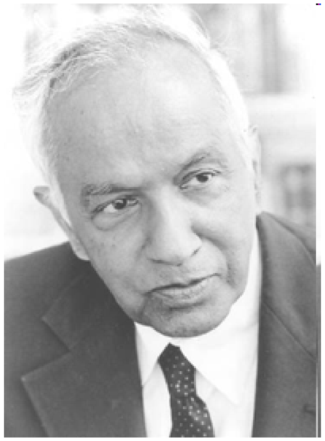




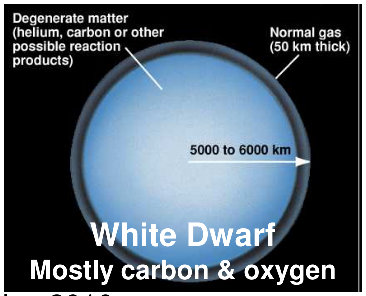




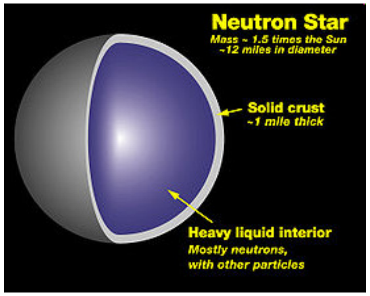
White Dwarfs and the Chandrasekhar Limit

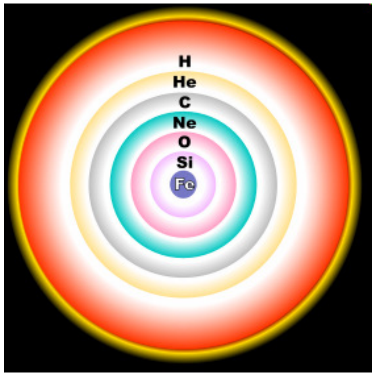


Subrahmanyan Chandrasekhar
1910 – 1995
Nobel Prize - Physics



- The Chandrasekhar limit, about 1.4 solar masses, is the maximum mass which can be supported against gravitational collapse by electron degeneracy pressure
- Electron degeneracy pressure is a quantum-mechanical effect of Pauli exclusion principle: no two electrons can be in the same state.
  - Analogous to Tolman–Oppenheimer–Volkoff limit, wherein gravity forces electrons into nuclei, forming a neutron star
- Initially, heat from fusion prevents gravitational collapse
  - A central core of nickel-iron builds up which cannot be fused, sustained only by degeneracy pressure
- For main-sequence stars with a ***total*** mass below ~ 8-9 solar masses, the ***core*** remains below the Chandrasekhar limit
  - Mass is lost by ejecting planetary nebulae until a white dwarf composed mostly of carbon and oxygen remains
- Stars with greater total mass develop a degenerate (non-fissionable) core whose mass grows until it explodes in a Type 2 core-collapse supernova
  - Leaves behind either a neutron star or a black hole (> 20 solar masses)

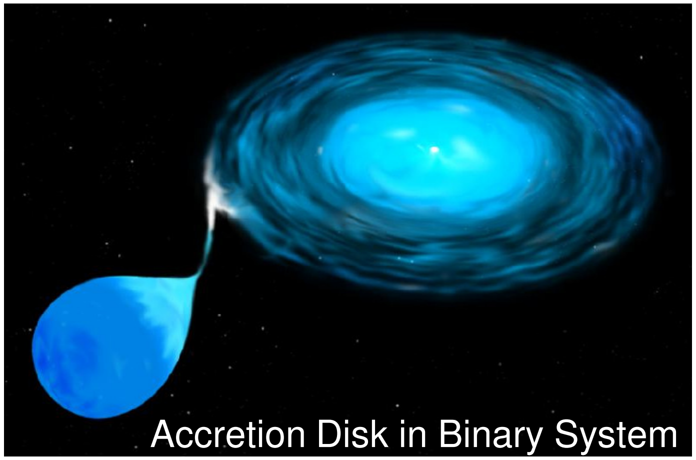




Star prior to core collapse

Wikipedia.com

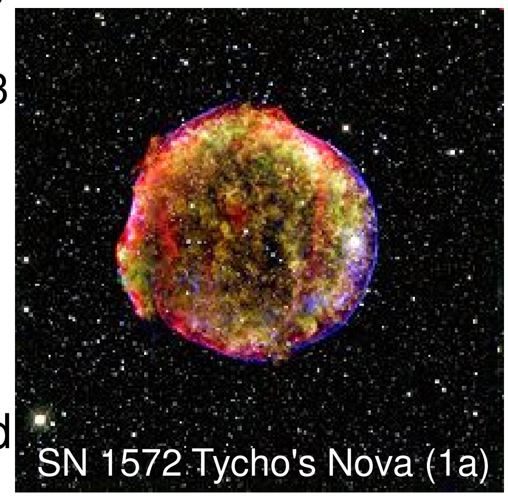
Type 1a Supernova as Standard Candle



Accretion Disk in Binary System

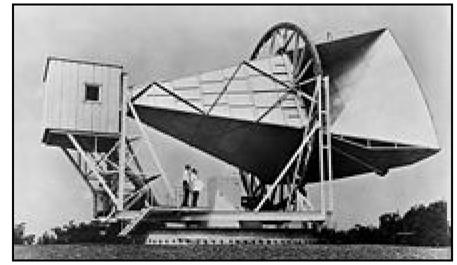
AstronomyNotes.com & Wikipedia.com
http://www.astronomynotes.com/evolutn/s11.htm

- Isolated white dwarfs will dim to black dwarfs
- But, a white dwarf close enough to a red giant or main sequence companion will accrete hydrogen-rich gas expelled by the companion
  - The gas will get compressed and heated by the white dwarf's gravity, eventually becoming dense enough for an explosive nuclear reaction
  - The gas is blasted outward in an expanding shell, producing a sudden burst of light
  - Early astronomers called them **novae** ("new")
- After the nova burst, gas from the companion begins to build up again, & the process repeats
- If the mass exceeds 1.4 solar masses, degenerate electrons will not stop gravity from collapsing the dead core
  - Mass transfer model first proposed by Whelan and Iben in 1973
  - Collapse heats carbon and oxygen nuclei to nuclear fusion temperatures, creating silicon nuclei, and from that nickel
- Enormous energy is released as the white dwarf blows itself apart This explosion is called a ***Type 1a supernova***
  - Formed from the collapse of a stellar core of a specific mass, **all Type 1a supernovae have similar luminosities**
- By the inverse square law, Type 1a supernovae can be used to **measure distances to distant galaxies**, out to several billion light years

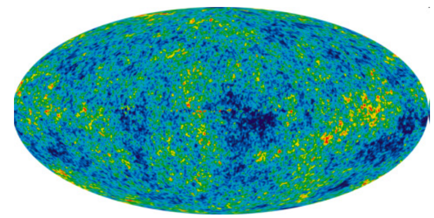


SN 1572 Tycho's Nova (1a)

Observable Universe



- The observable universe consists of the matter we can see (galaxies, gas, planets, etc.) because its light has had time to reach us since it condensed from the Big Bang
  - The universe is likely bigger than we can ever observe. Some parts may never have been close enough for light to overcome the speed of expansion
- The most distant radiation is the **cosmic microwave background radiation**, predicted by Gamow, Alpher and Herman in 1948 and found by **Arno Penzias and Robert Wilson** in 1964 (Nobel Prize)
  - First atomic nuclei formed roughly 3-20 minutes after the Big Bang
  - First atoms formed about 380,00 years after the Big Bang, gave rise to CMBR

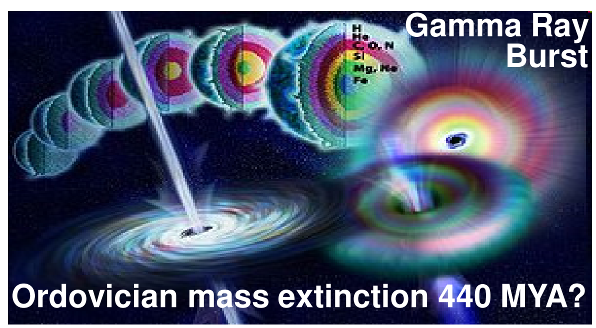


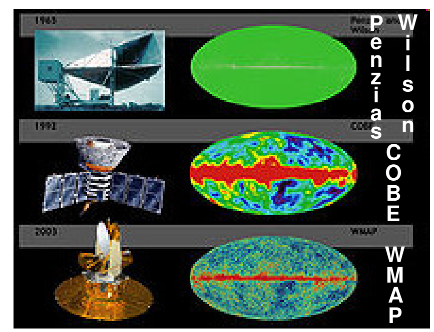
WMAP image of the CMBR

Hubble Ultra Deep Field (Fornax)

- The age of the universe is about 13.7 billion years
  - Based on cosmic background radiation, expansion of the universe, white dwarf temperature, and gamma ray bursts
    - **The most distant object observed is a gamma ray burst (2009), likely from a collapsing star when the universe was 600 million years old**
    - **Oldest star found in Milky Way is HE 1523, at 13.2 billion years old**
    - **First galaxies formed one-half to one billion years after the Big Bang**
  - The most accurate observation of cosmic background microwave radiation is from NASA's Wilkinson Microwave Anisotropy Probe

- The present radius of the observable universe is ~46 billion light years, not 13.7 billion LY
  - The light we see today from the edge of the visible universe left 13.7 billion years ago, but the universe has expanded since then



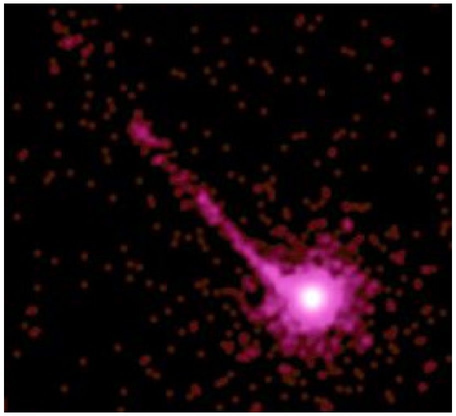


Quasars

- A **quasar** (quasi-stellar radio source) is a very energetic and distant galaxy with an active galactic nucleus
  - Discovered in late 1950s by radio telescopes
    - Quasars were first identified as sources of high redshift electromagnetic energy, including radio waves and visible light
  - Most quasars are farther than three billion light-years away
  - They are the most luminous objects in the universe; some radiate at a rate exceeding the output of average galaxies

John Bolton

- Quasars are believed to be powered by accretion of material into supermassive black holes in the nuclei of distant galaxies
  - Quasars are point-like, similar to stars, rather than extended sources
  - Some quasars display changes in luminosity which are rapid in the optical range and even more rapid in X-rays
    - Vary in brightness over months, weeks, days, or hours
  - This implies that they are small (Solar System sized or less) because an object cannot change faster than the time for light to travel from one end to the other

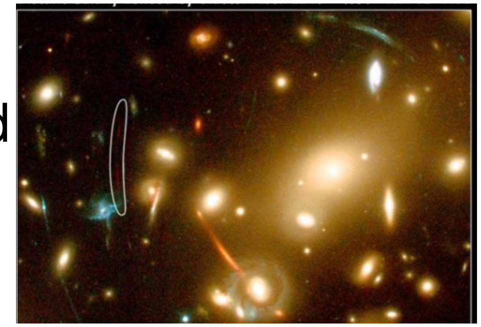


  - Small size makes them useful for gravitational lensing studies
  - Quasars 'turn on' and off depending on their surroundings
  - Since quasars cannot continue to feed at high rates for 10 billion years, after a quasar finishes accreting the surrounding gas and dust, it becomes an ordinary galaxy
  - The quasar that appears brightest in our sky is 3C 273 in the constellation Virgo, with an apparent magnitude of 12.8
    - Bright enough to be seen through a medium-size amateur telescope

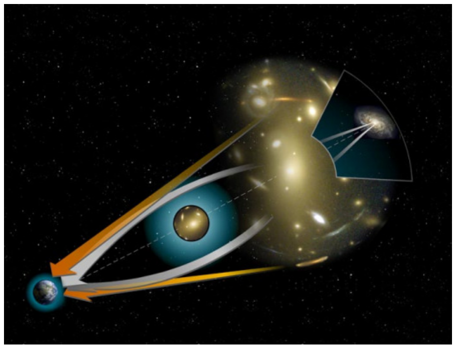
Wikipedia.com

Gravitational Lensing

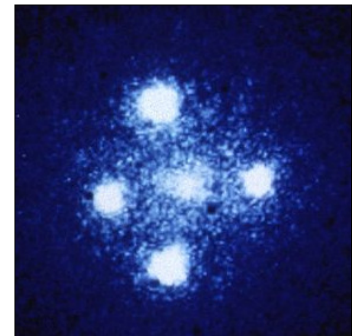
Distant galaxy lensed by Abell 2218



- A gravitational lens is formed when the light from a very distant bright source (such as a quasar) is “bent” around a massive object, e.g. a galaxy cluster (or black hole)

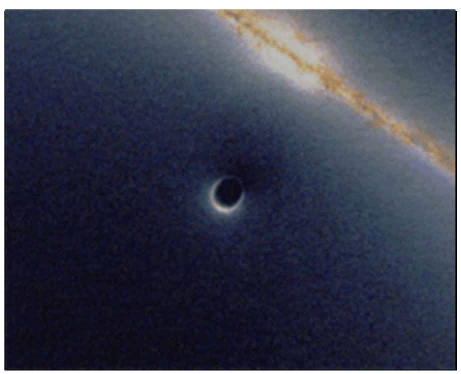


  - Orest Chwolson wrote first paper in 1924, Einstein followed in 1936
  - Fritz Zwicky posited that a galaxy cluster could act as a GL in 1937
  - First gravitational lens seen in 1979: "Twin QSO" SBS 0957+561
    - Einstein rings & arcs and multiple images

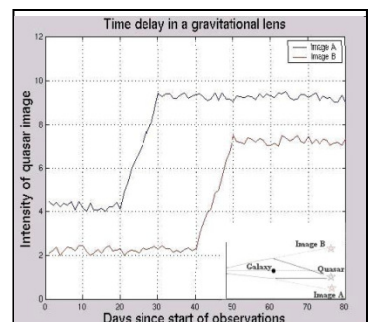


Einstein’s Cross In Pegasus (400MLY / 8BLY)

- Gravitational lensing can be used to assist in quantifying the expansion history of the universe
  - Measurements can help reconstruct the background distribution of dark matter around a galaxy cluster
  - Lensed quasar distances can be determined and can quantify variations from Hubble’s Constant due to dark energy



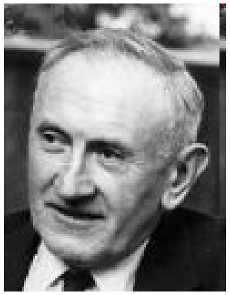
- Time delays between lensed images (due to optical path length and relativistic effects)
- Angular separation of the different images from the lensing foreground object
- Relative distance of lens and source, via redshift
- Mass & distribution of the lensing object



Time delay in a gravitational lens

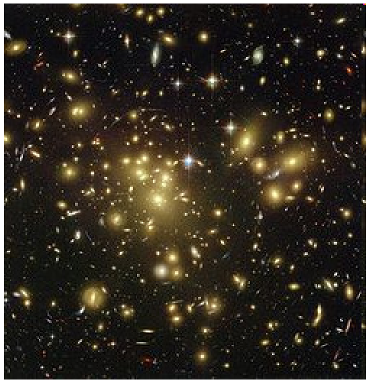
http://universe-review.ca/R02-07-candle.htm & wikipedia.com

Evidence of Dark Matter



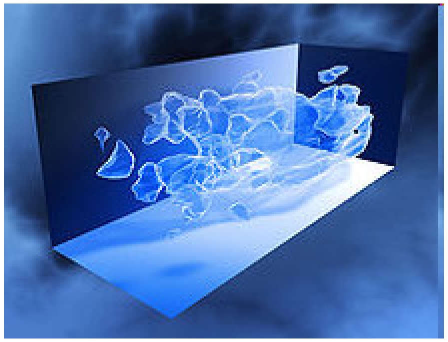
Fritz Zwicky
1898-1974
Astrophysicist

- "Dark matter" was first postulated by Fritz Zwicky in 1934 to account for evidence of missing mass in the orbital velocity of galaxies in clusters.
  - Other subsequent evidence included galaxy rotational speed and gravitational lensing
  - Dark matter evidently plays a key role in galaxy and galaxy cluster formation & evolution



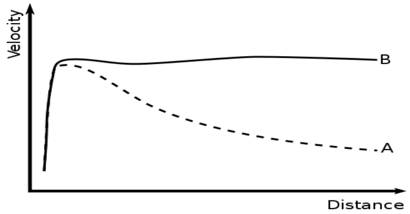
Gravitational lensing (HST)

- In the late 1960s and early 1970s Vera Rubin at the Carnegie Institution found anomalous rotational velocity curves in edge-on spiral galaxies using spectrograph data
  - Rubin and colleague Kent Ford presented the results at the 1975 meeting of the American Astronomical Society
  - Implication is that either Newtonian gravity is not invariant or that > 50% of all galactic mass is contained in a dark halo
  - Oddly, Rubin initially supported the MOND interpretation!!



Model of dark matter distribution

- A number of underground experiments are trying to detect dark matter via interactions



Rotation curve of typical spiral galaxy: (**A**) predicted (**B**) observed. Dark matter can explain the velocity curve being 'flat' out to a large radius

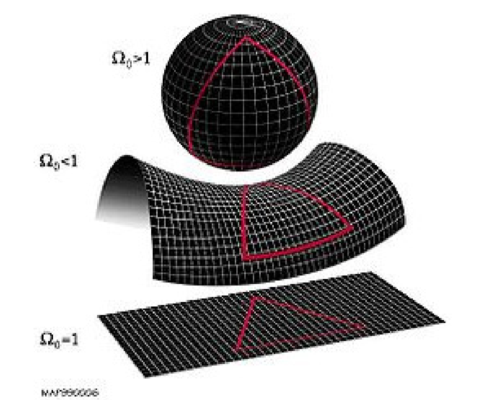
Vera Rubin measuring spectra

- One of the goals of CERN's Large Hadron Collider is to find proof of dark matter (WIMPS!)

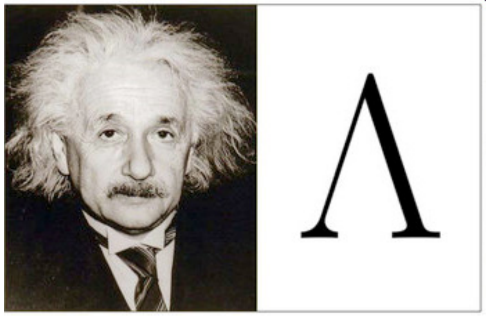
Wikipedia.com

Dark Energy – the Next Great Mystery?

- Measurements of the cosmic microwave background indicate that the Universe has a flat geometry (density profile) on large scales. The difference can be attributed to "dark energy"
  - The total amount of matter in the universe (visible and dark) accounts for only about 25% of the critical density needed to make the Universe flat
  - The theory of large scale structure, up to and including galaxy superclusters and filaments, also suggests that the density of matter in the universe is only 30% of the critical density
  - The Sachs-Wolfe Effect is consistent with dark energy: hot and cold spots in the CMBR align with observed galaxy superclusters, supervoids and filaments



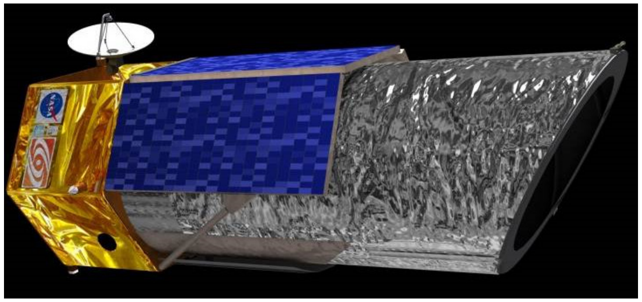
The local geometry of the universe is determined by whether the relative density Ω is less than, equal to or greater than 1. Our universe is flat, with almost exactly the critical density (Ω=1, k=0).



- Some astronomers identify dark energy with Einstein's Cosmological Constant, introduced into general relativity (1915) to negate its pre-Hubble prediction of an unstable universe
  - Later, some physicists came to associate the constant with quantum vacuum energy effects

http://hubblesite.org/hubble_discoveries/dark_energy/de-what_is_dark_energy.php
http://imagine.gsfc.nasa.gov/docs/science/mysteries_l1/dark_energy.html

- Alan Guth in the 1970s proposed the concept of a negative pressure field, similar in concept to dark energy, to drive **cosmic inflation** in the early stages of the Big Bang
  - However, cosmic inflation must occur at higher energy levels than the dark energy observed today
  - Cosmic Inflation is thought to have ended soon after the Big Bang
  - NASA is building the Dark Energy Space Telescope (Destiny) to research dark energy



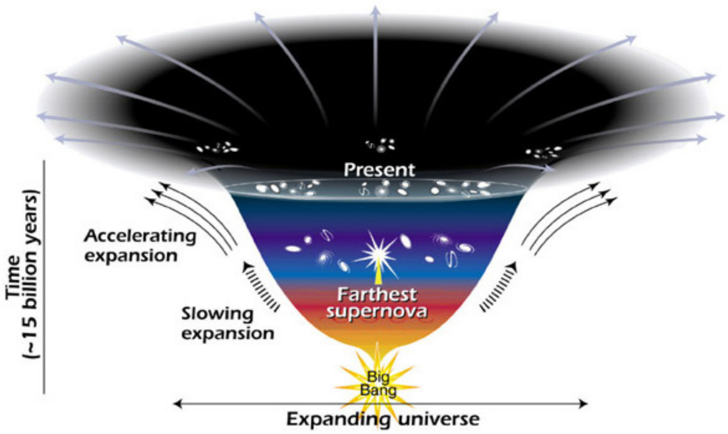
Wikipedia.com

Evidence of Dark Energy

- Edwin Hubble showed that the Universe is expanding; in 1998 it was discovered that the rate of expansion is actually increasing!
  - This was a shock; astronomers had long believed that the initial expansion from the Big Bang was being slowed by gravity

High-Z Supernova Search Team

SCP's Saul Perlmutter

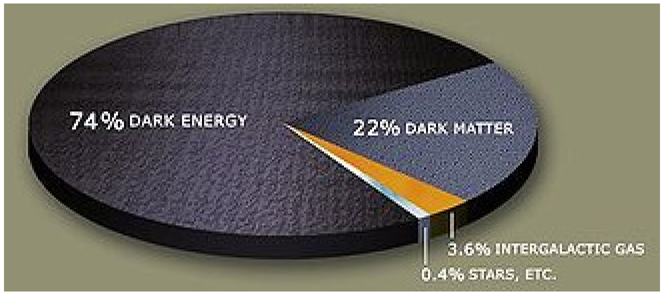


http://www.space.com/scienceastronomy/astronomy/cosmic_darknrg_020115-1.html

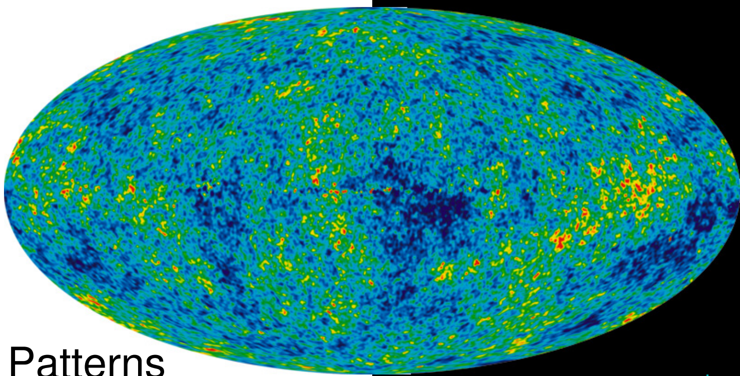
NASA/A. Riess

- In the 1990's two teams, the High-Z Supernova Search and the Supernova Cosmology Project observed Type 1a supernovae to measure the expansion rate over time.
  - The distance to type 1a supernovae determines how long ago they occurred
  - In addition, their light has been red-shifted by the expansion of the Universe. The redshift tells how much the Universe has expanded since the Big Bang
  - By studying many supernovae at different distances, each team intended to piece together a history of the expansion of the Universe
  - Instead of slowing, they found that expansion is accelerating! (1998) They called this **"dark energy"**

- Unlike dark matter, which has gravitational effects on visible matter, little is known about dark energy; it merely gives a name to the mystery of accelerating expansion
  - It is very homogeneous, not very dense and does not interact through any force other than gravity
  - Dark energy accounts for 74% of the Universe, dark matter 22%, and visible matter and energy 4%

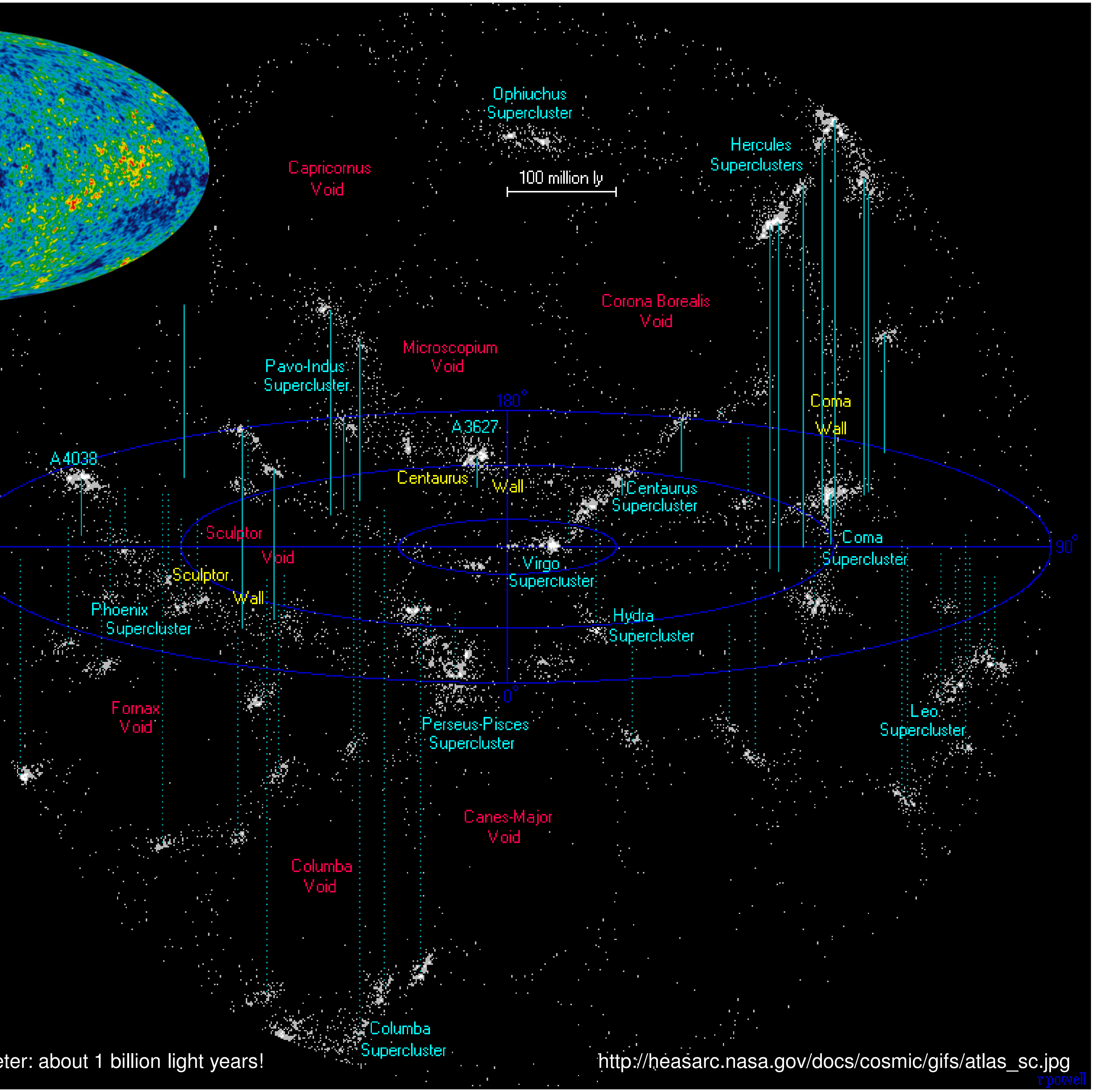


http://hubblesite.org/hubble_discoveries/dark_energy/de-what_is_dark_energy.php
http://imagine.gsfc.nasa.gov/docs/science/mysteries_l1/dark_energy.html
http://www.cfa.harvard.edu/supernova//home.html & http://supernova.lbl.gov/

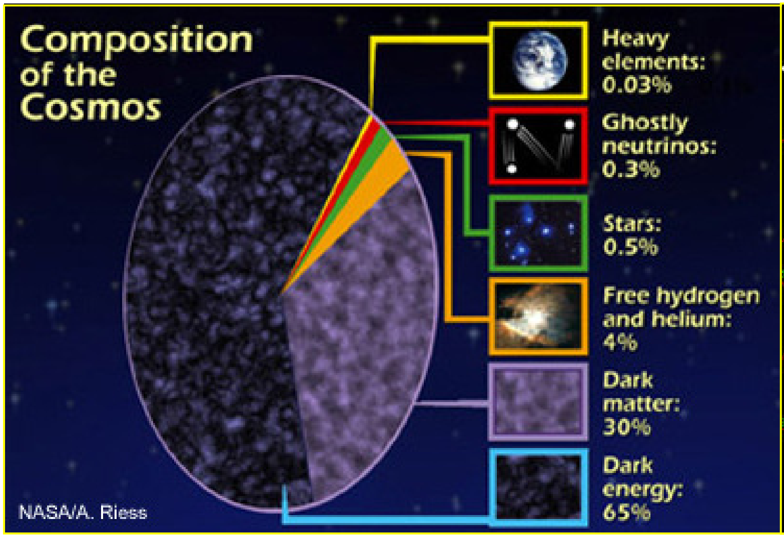


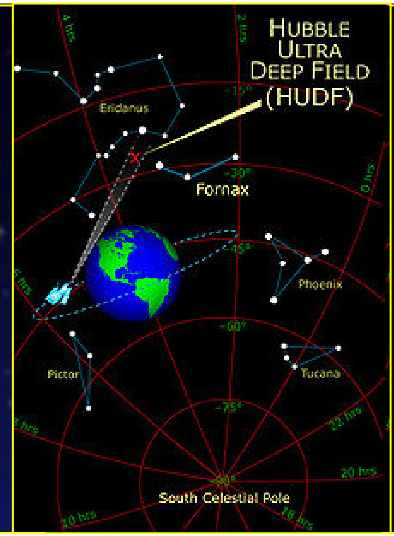
Patterns of infinitesimally small temperature and density variations in the cosmic microwave background radiation (10^{-5}), left over from the time of the Big Bang, have led to filaments and walls of galaxy super clusters and super voids stretching billions of light years, the largest structures in the observable Universe

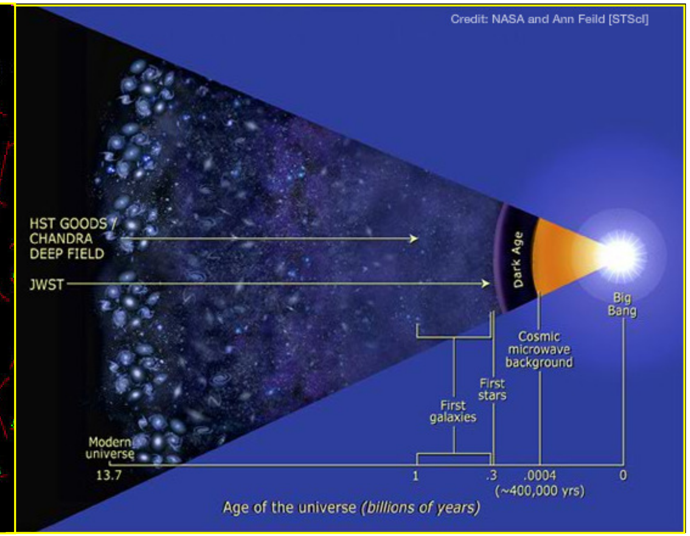
Nov 2010 Wikipedia.com



Questions & Answers







Fair Use Notice

In accord with Title 17 U.S.C. Sections 107-118, all copyrighted material herein is reproduced under fair use without profit or payment and is intended solely for the benefit of those receiving the information for non-profit research and educational purposes only.

[Reference: http://www.copyright.gov/fls/fl102.html, May 2009]

Never point a telescope at the sun
– unless it's a solar telescope, of course!!
. . .and don't look into the laser pointer either!!