Per ardua ad astra

Through adversity to the stars

Ad astra per aspera

Through hardships, to the stars

Measuring the Universe

by

Tony Heyes

Twinkle, twinkle little star,

How I wonder what you are.

1806

- Perfectly reasonable
- Stars could well have been all the same distance away supported on a celestial sphere, or
- Perhaps pinpricks in the black celestial sphere beyond which was the realm of both Heaven, Hell and the Angels

1835

"There is no conceivable means by which we shall one day determine the chemical composition of the stars"

Auguste Comte (1798 – 1857)

1838

Friedrich Bessel

(1784 – 1846)

measured the *distance* to a star

The use of parallax

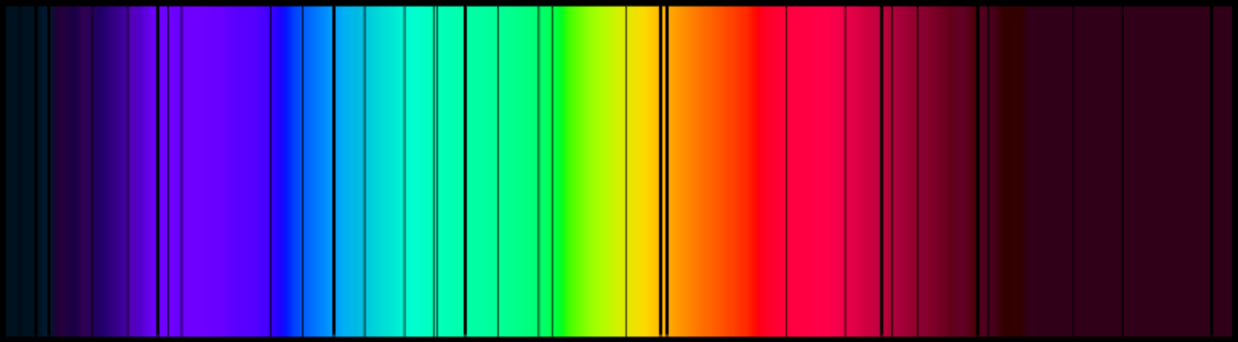
- Bessel found that *some* stars *moved* against the background of more distant stars
- Stars were NOT all the same distance away!

William Hyde Wollaston in 1802

and

Joseph von Fraunhofer in 1814

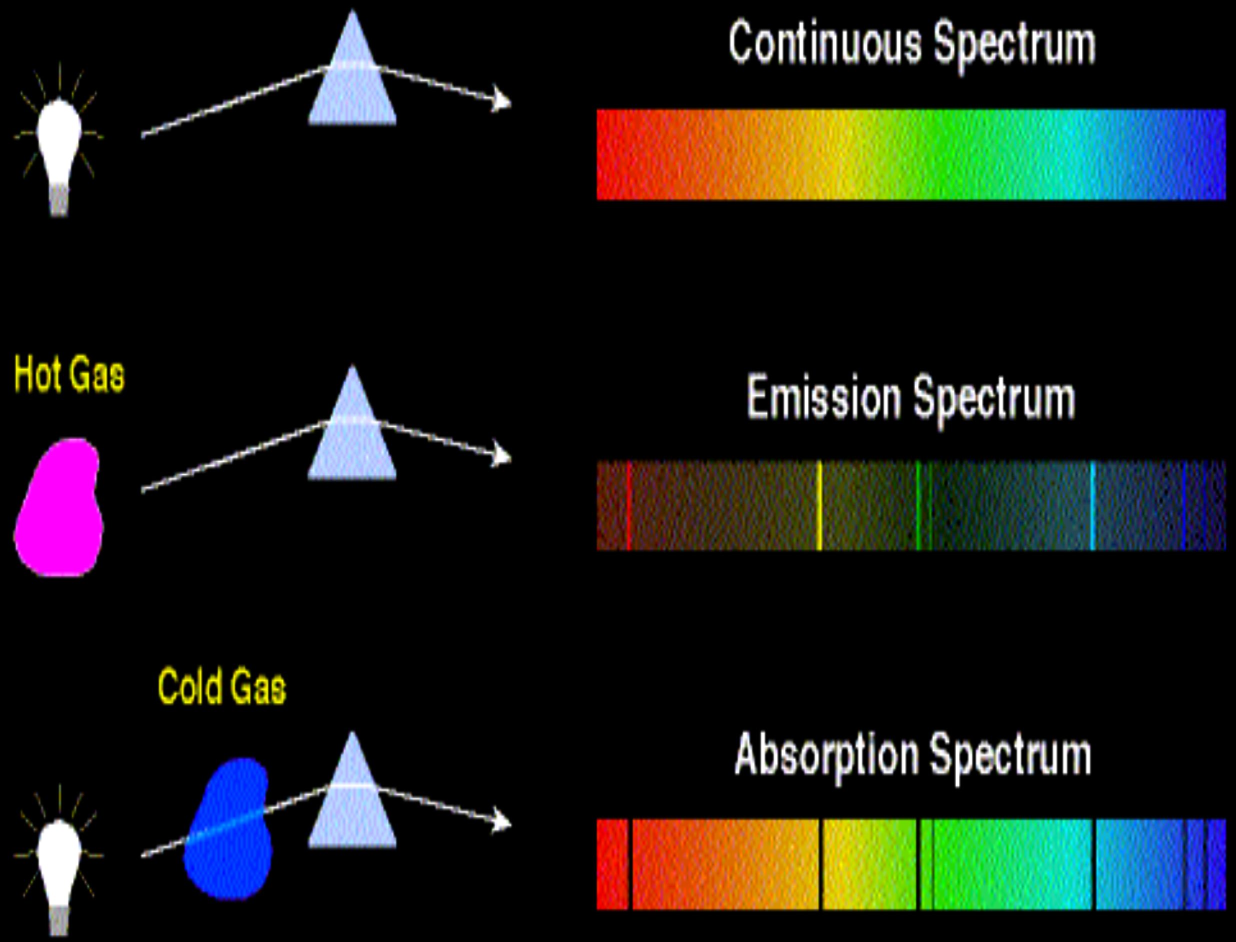
Observed spectral absorption lines (*Fraunhofer Lines*) in the sun



1859

Two years after Compte's death Kirchhoff and Bunsen noticed that several Fraunhofer lines coincide with characteristic emission lines identified in the spectra of heated elements

This discovery enabled scientists to determine the *chemical composition* of stars



Continuous Spectrum
Hot Gas
Emission Spectrum
Cold Gas
Absorption Spectrum

The element Helium was discovered in the sun *before* it was found on earth

Hence the name

And we now know that with the exception of the four lightest elements Hydrogen, Helium, Lithium and Beryllium

ALL

the other atoms, including those in our bodies, were synthesised in stars

The fact that *we are* made of *star stuff* is,
to me, the most exciting finding of all time

Discovering the mechanism of evolution
from *star stuff* to intelligent life is one
of the main goals of science

- 1806 Twinkle, twinkle little star
  How I wonder what you are
- 1835 Compte
- 1838 Bessel (Distance)
- 1859 Kirchoff & Bunsen
  (Chemistry)

So we *are* making progress

We do it by taking small, humble, steps

So let’s make a start

How would you measure the height of a bridge tower?

- Using:
- A barometer
- A stopwatch
- A ball of string
- A tape measure
- A broom handle
- A mallet

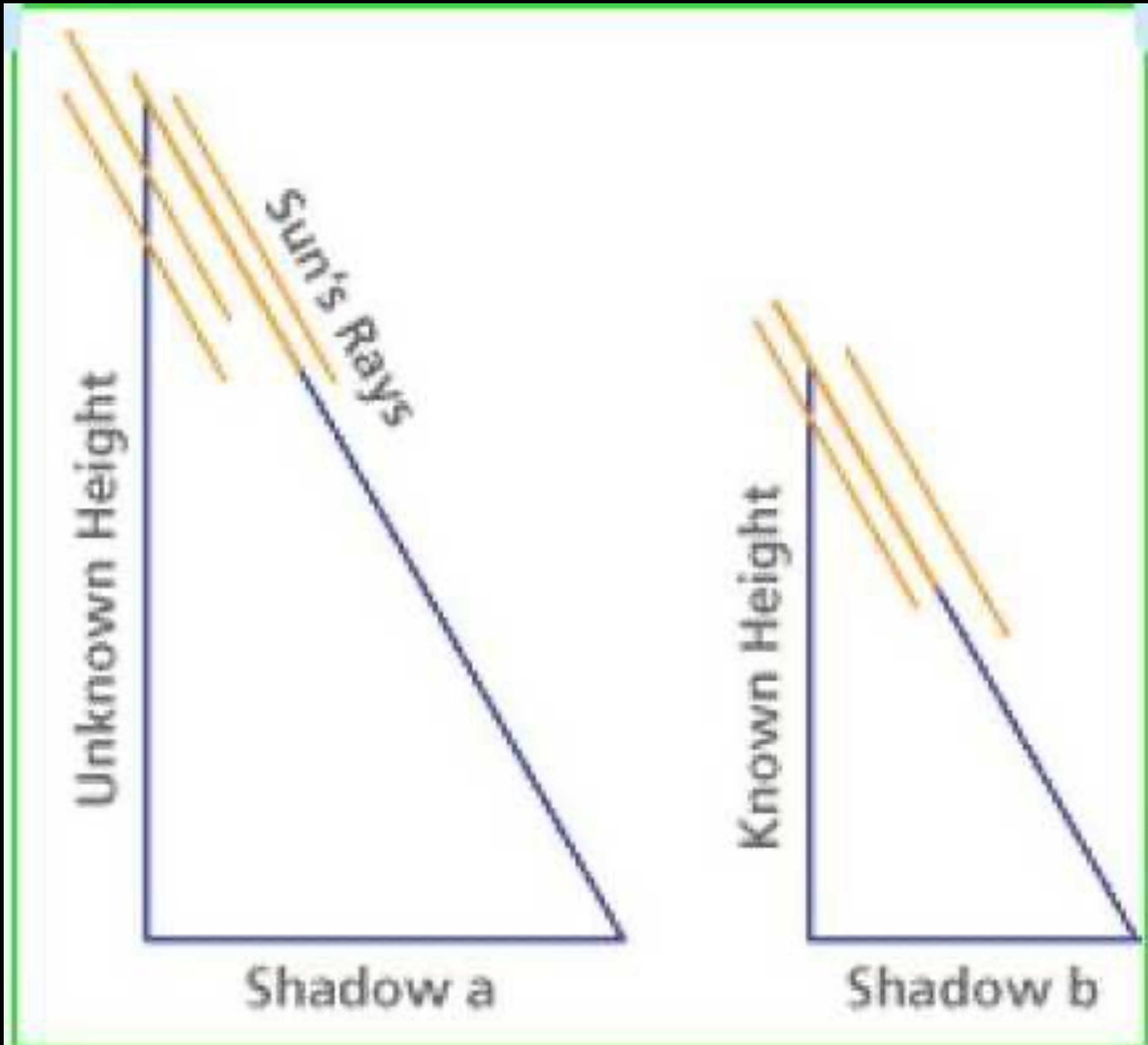
Millau Viaduct

- We could take the barometer to the top of the tower, throw it off, and use the stop watch to time how long it took to hit the ground

- We could tie the mallet to the end of the string and lower it from the top

or

- We could use the broom handle, the mallet, the tape measure and sunlight.



Sun's Rays
Unknown Height
Known Height
Shadow a
Shadow b

In the beginning....

There were the Greeks

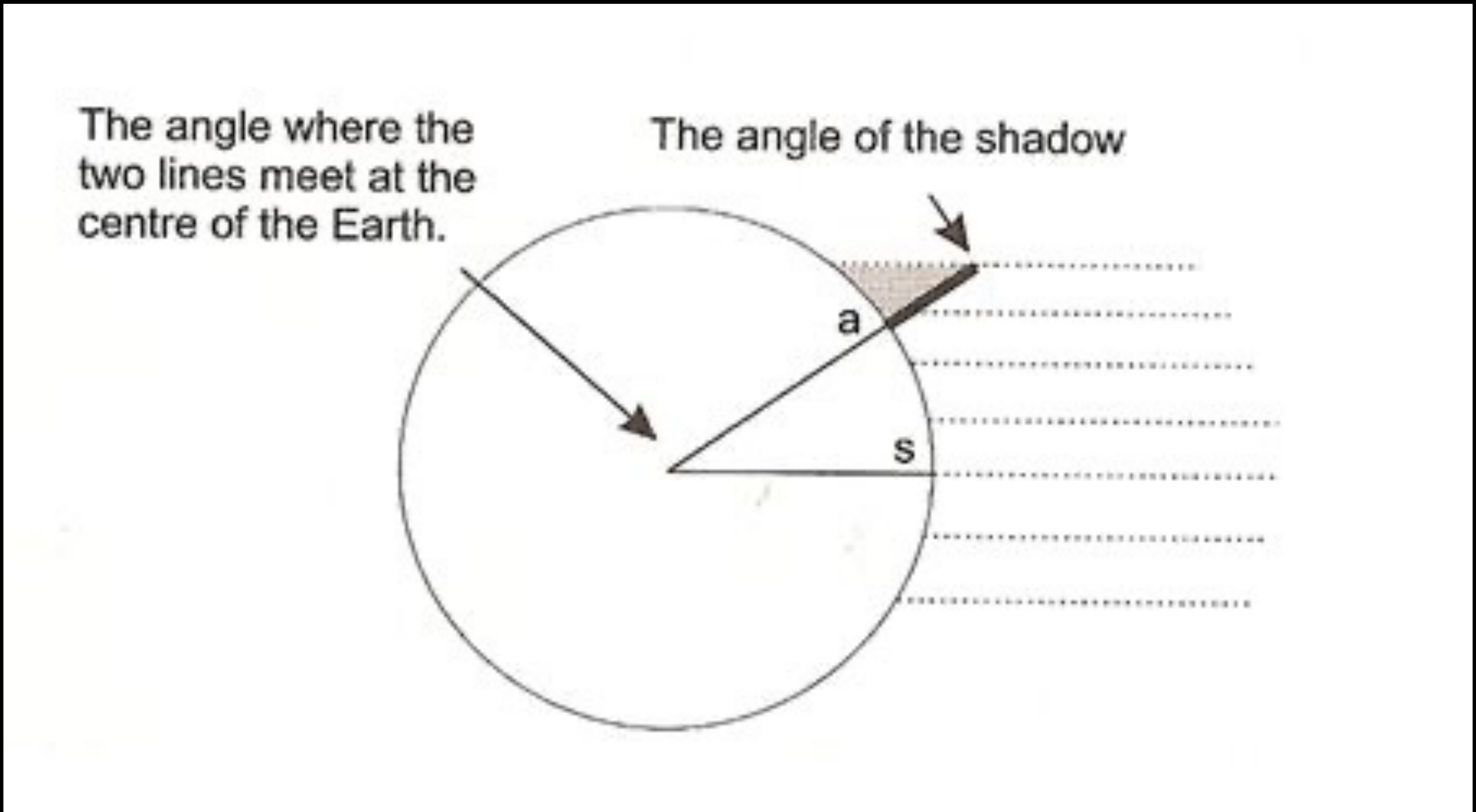
Aristarchus (c. 310 - 230 BC)

(Arry-star-cus)

Eratosthenes (c. 273 - 195 BC)

(Era-toss-the-knees)

Eratosthenes (c. 273 – 195 BC)



Eratosthenes (c. 273 – 195 BC)

- Eratosthenes calculated the shadow angle to be 7° 12' or just 1/50 of a full circle. Thus he multiplied his distance from Syene (Aswan) to Alexandra by 50 and thereby obtained the circumference of the earth.
- He obtained 39,690 km, an error of less than 1%.

And then there were the Arabs

Abū Rayḥān Muḥammad ibn Aḥmad Bīrūnī {Al Beruni} (973 – 1048)

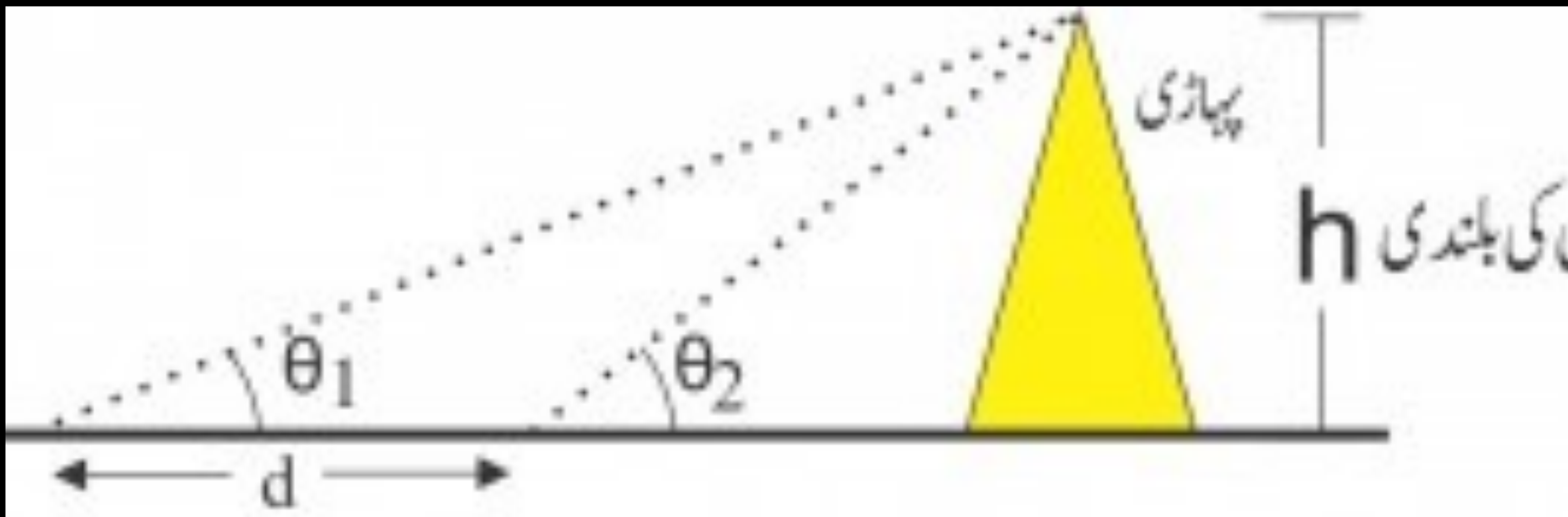
Also measured the diameter of the Earth

Al Beruni (973 – 1048)

Al Beruni (973 – 1048)

First he measured the height of a mountain

Al Beruni (973 – 1048)

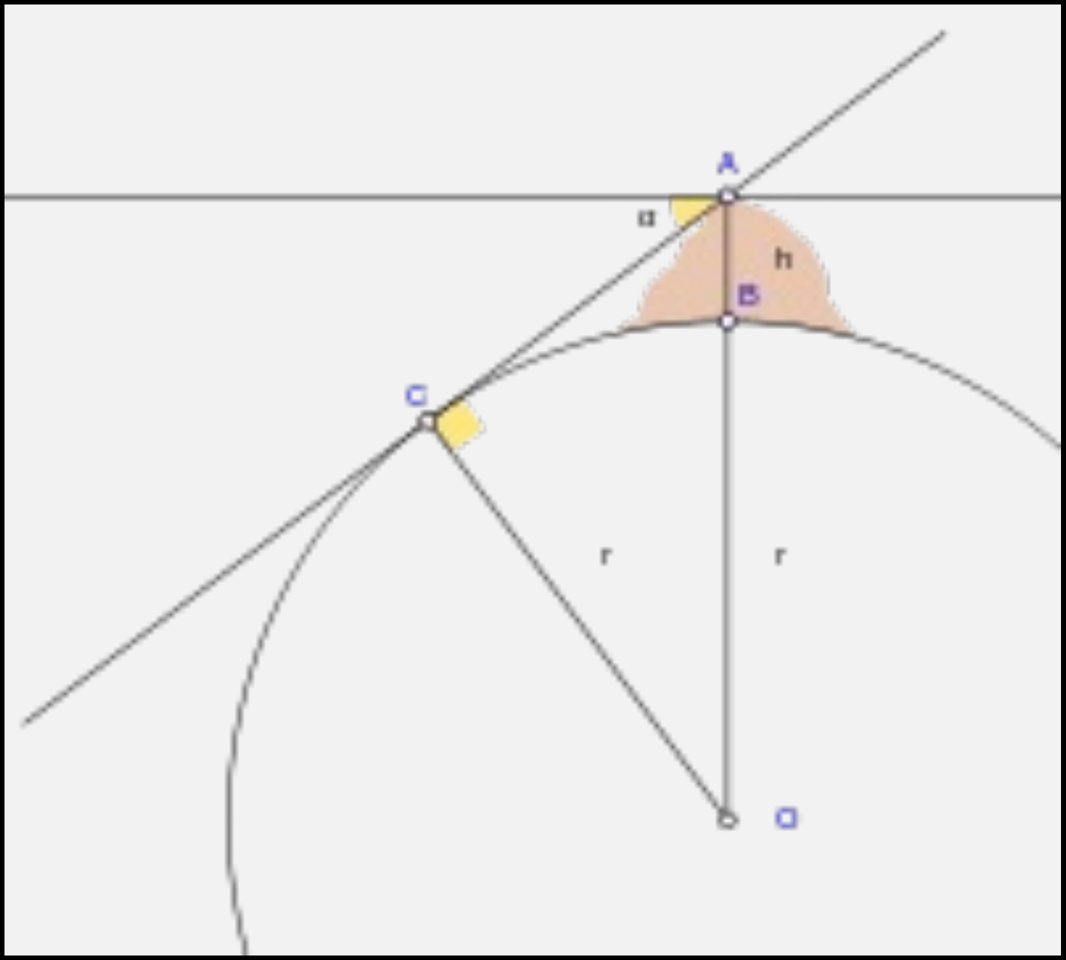


$$h = \frac{d\tan\theta_1\tan\theta_2}{\tan\theta_2 - \tan\theta_1}$$

Al Beruni (973 – 1048)

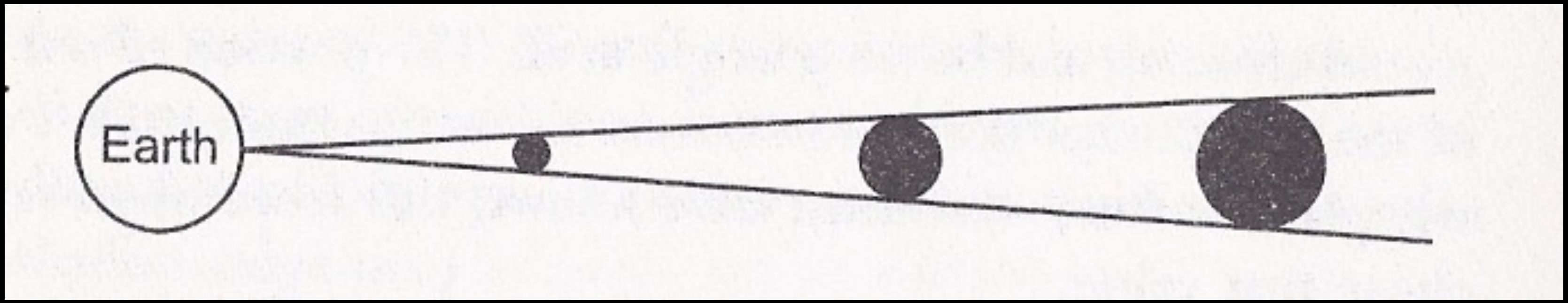
Then he climbed the mountain and measured the angle between the horizontal and the horizon

Al Beruni (973 – 1048)



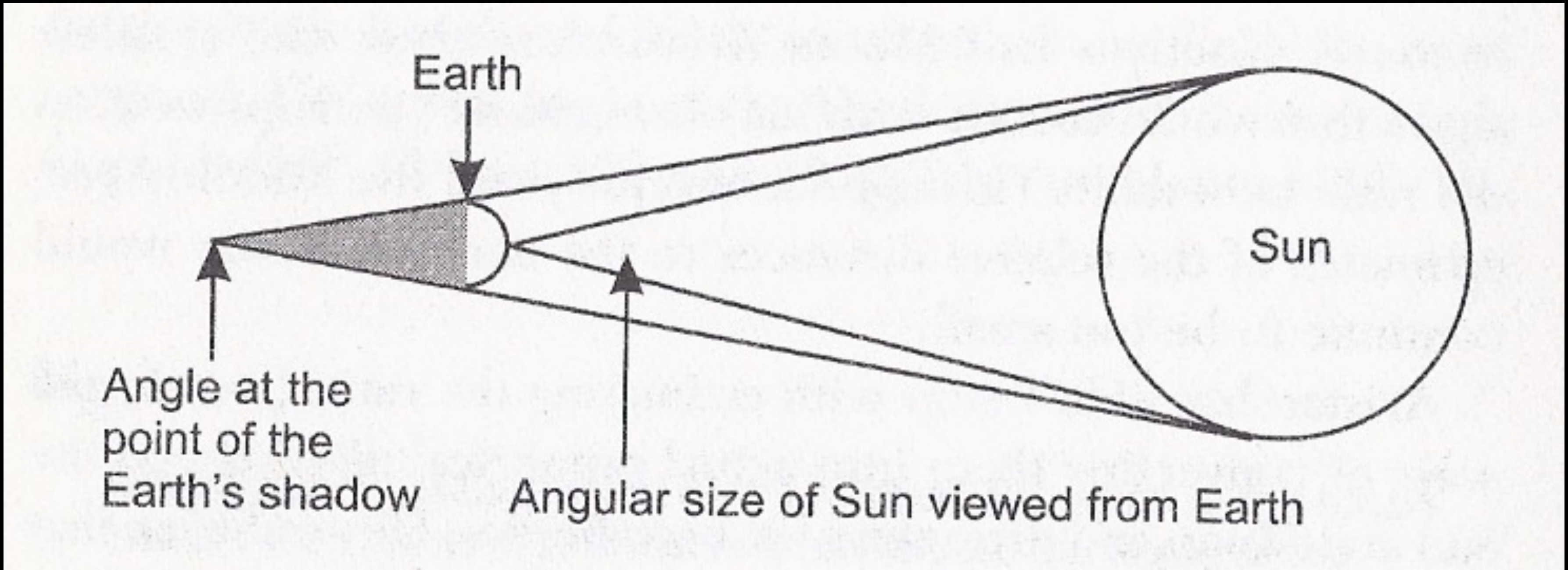
Back to the Greeks

Aristarchus observed that the Sun and the Moon had the same *apparent* size

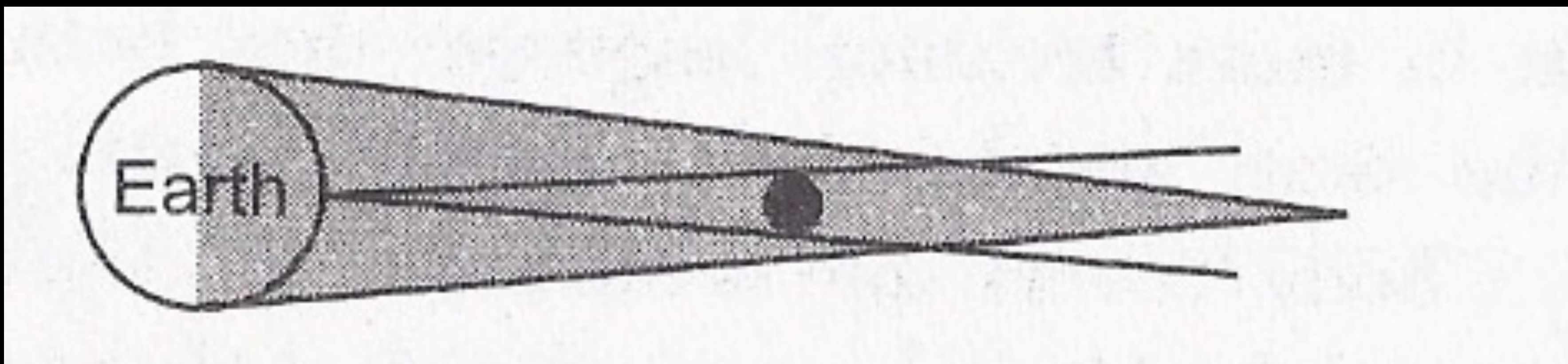


Aristarchus argued that since the Sun is much larger than the Moon and much further away,

the angle at the point of the Earth's shadow would be approximately equal to the angular size of the Sun


Earth
Sun
Angle at the point of the Earth's shadow
Angular size of Sun viewed from Earth

Aristarchus noted that during an eclipse of the Moon, the breadth of the Earth’s shadow crossed by the Moon was approximately twice the diameter of the Moon


Earth

Aristarchus noted that only one Earth – Moon distance would satisfy this condition.

The case when:

The Moon is ¼ the size of the Earth

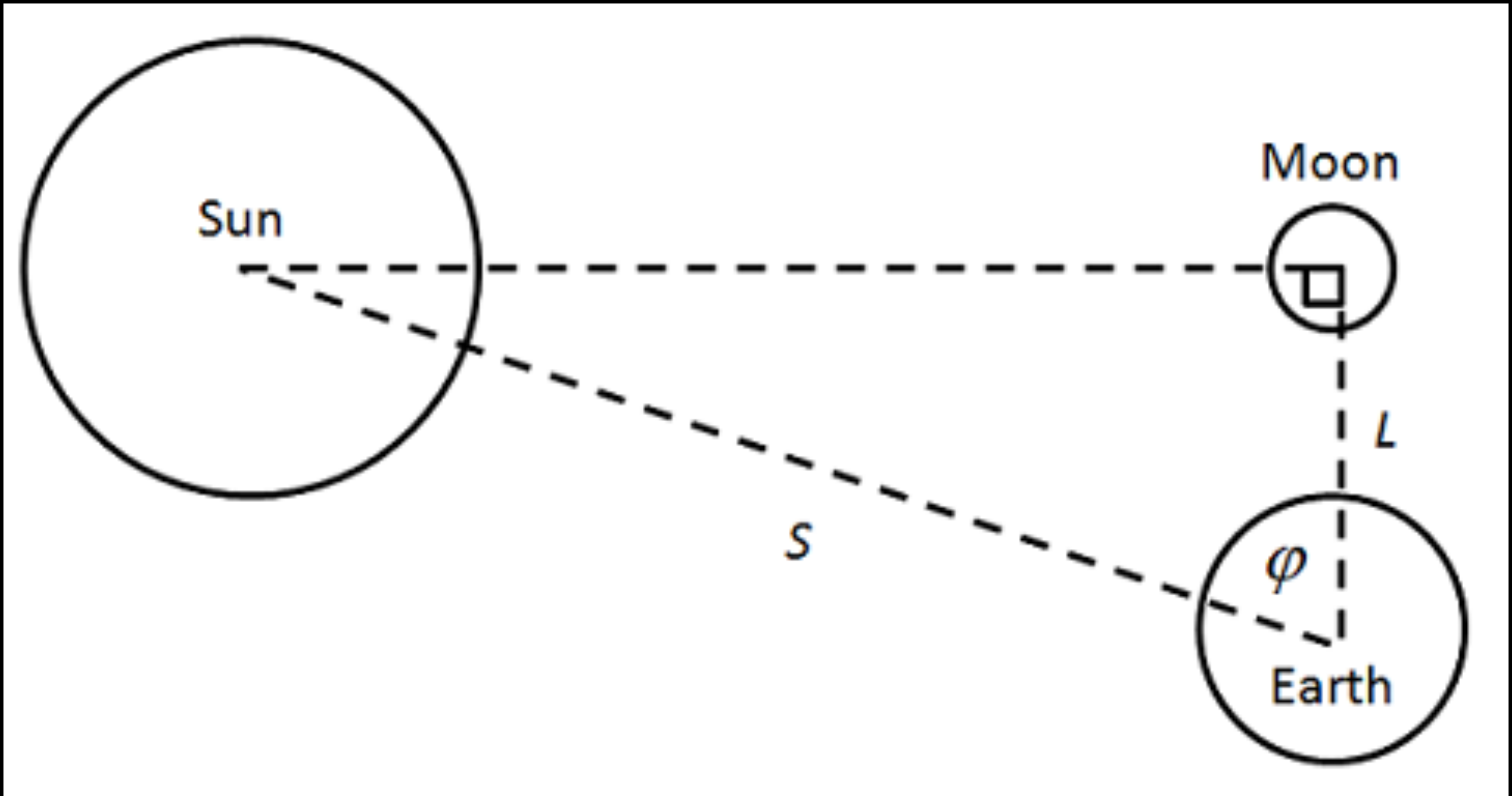
and

The distance to the Moon is 60 times the Earth's radius

Aristarchus also had a go at determining the distance to the Sun

He had to make a measurement at exactly the moment of “half” moon

Aristarchus (c. 310-230 BC)



Aristarchus estimated the angle to be 87°

It should have been 89° 52 ‘

Aristarchus’s calculated the ratio of the Sun’s distance to Moon’s distance to be 19

It should have been 400

Notice that ALL

Aristarchus's numbers were relative values, ratios, all in terms of the size of the Earth.

BUT

Put together with Eratosthenes's absolute value for the diameter of the Earth we get absolute values

Notice that

Relative values become absolute values when one value is known

These two Greek gentlemen had measured:

the diameter of the Earth

the diameter of the Moon

the distance to the Moon

the distance to the Sun

- Aristarchus (310 – 230 BC) also had the audacity to suggest that the Earth rotated about the Sun
- He was supported by:
- Archimedes (287 – 212 BC)
- Erotosthenes (276 – 194 BC)
- Hipparchus (190 – 120 BC)

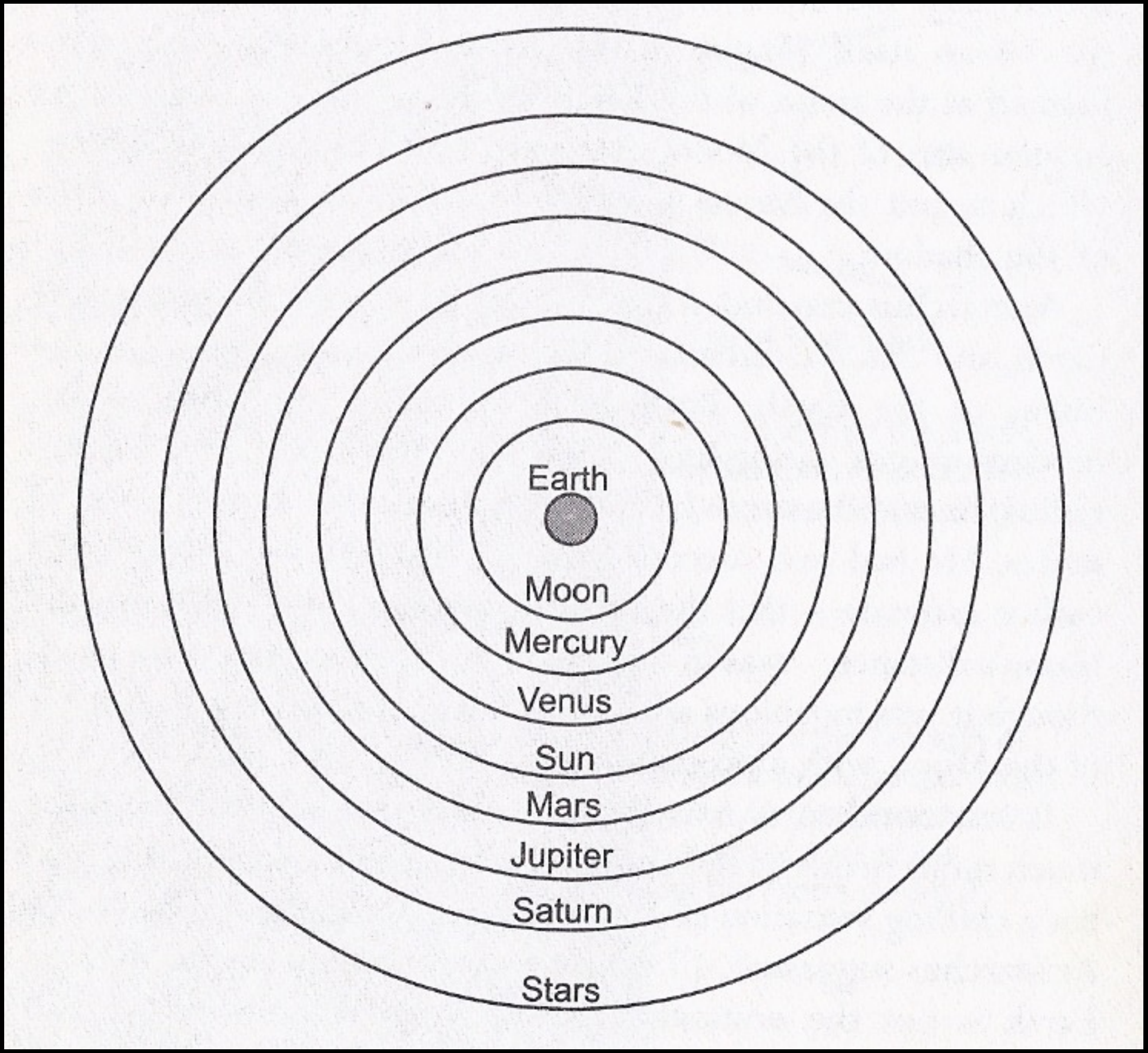
Aristotle (c. 384 - 322 BC) had said otherwise!

And then there was……..

Ptolemy （c. 100 – 170 A.D.）

- The Sun, the Moon and all the “wandering stars” all move in perfect circles around the Earth.
- The Stars are all the same distance away supported on a celestial sphere.

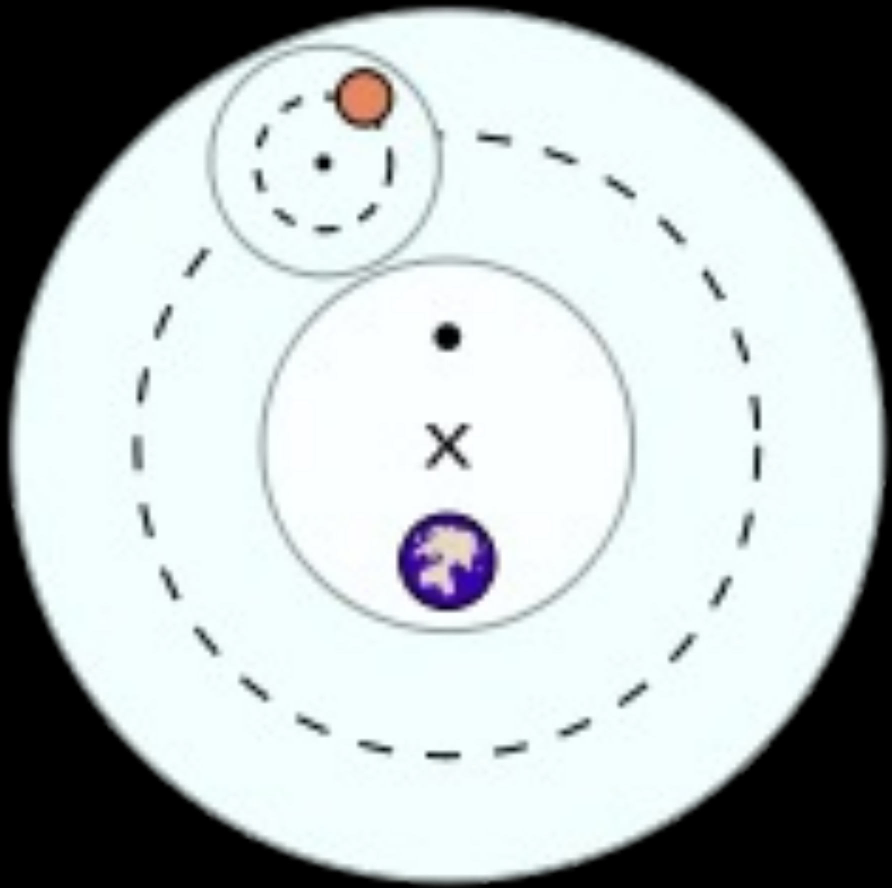
Ptolemy (c. 100 - 170 A.D.)



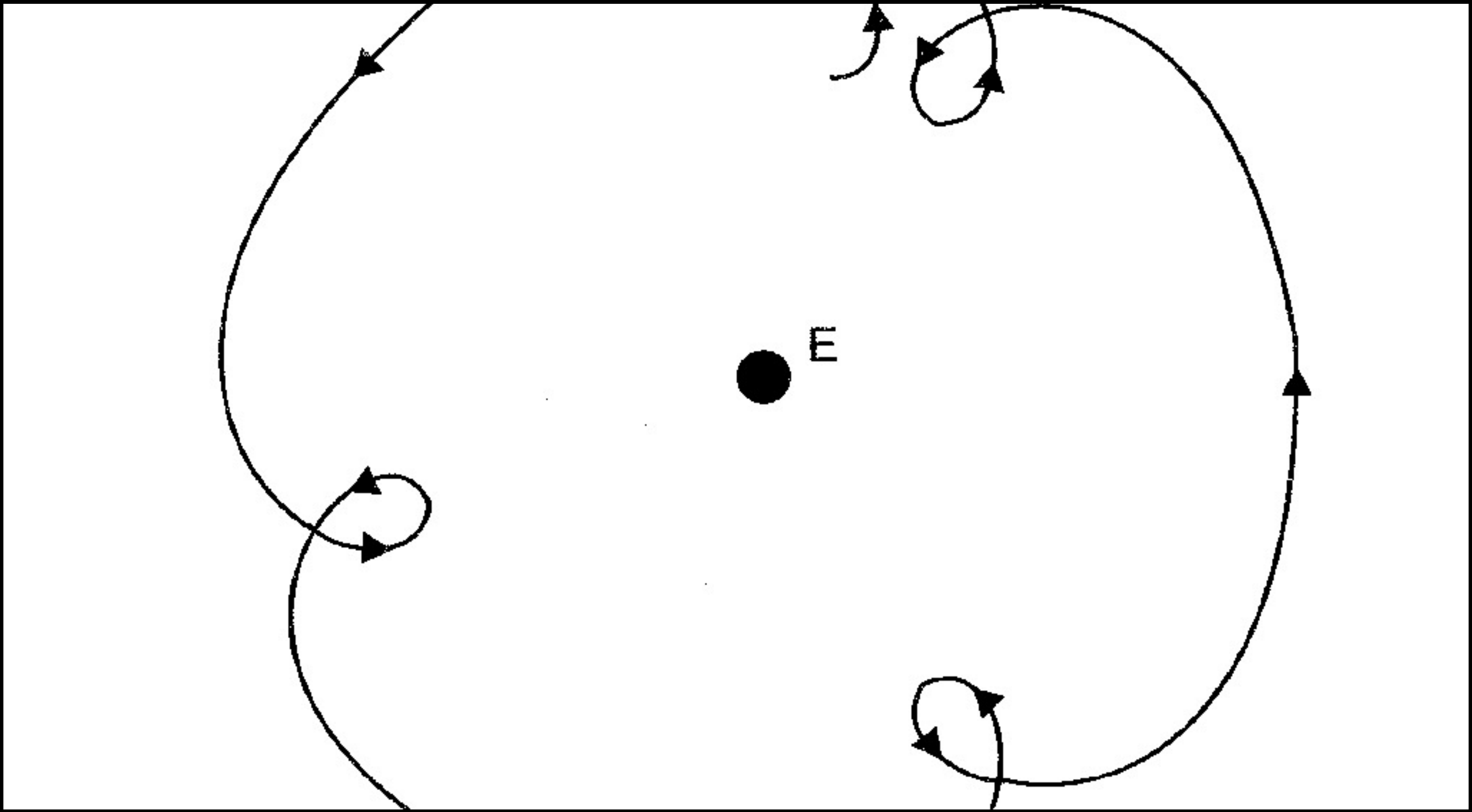
Ptolemy (c. 100 – 170 A.D.)

- But the Planets – the Wandering Stars – did not always do the right thing!
- Sometimes they *even* went backwards - *retrogression*

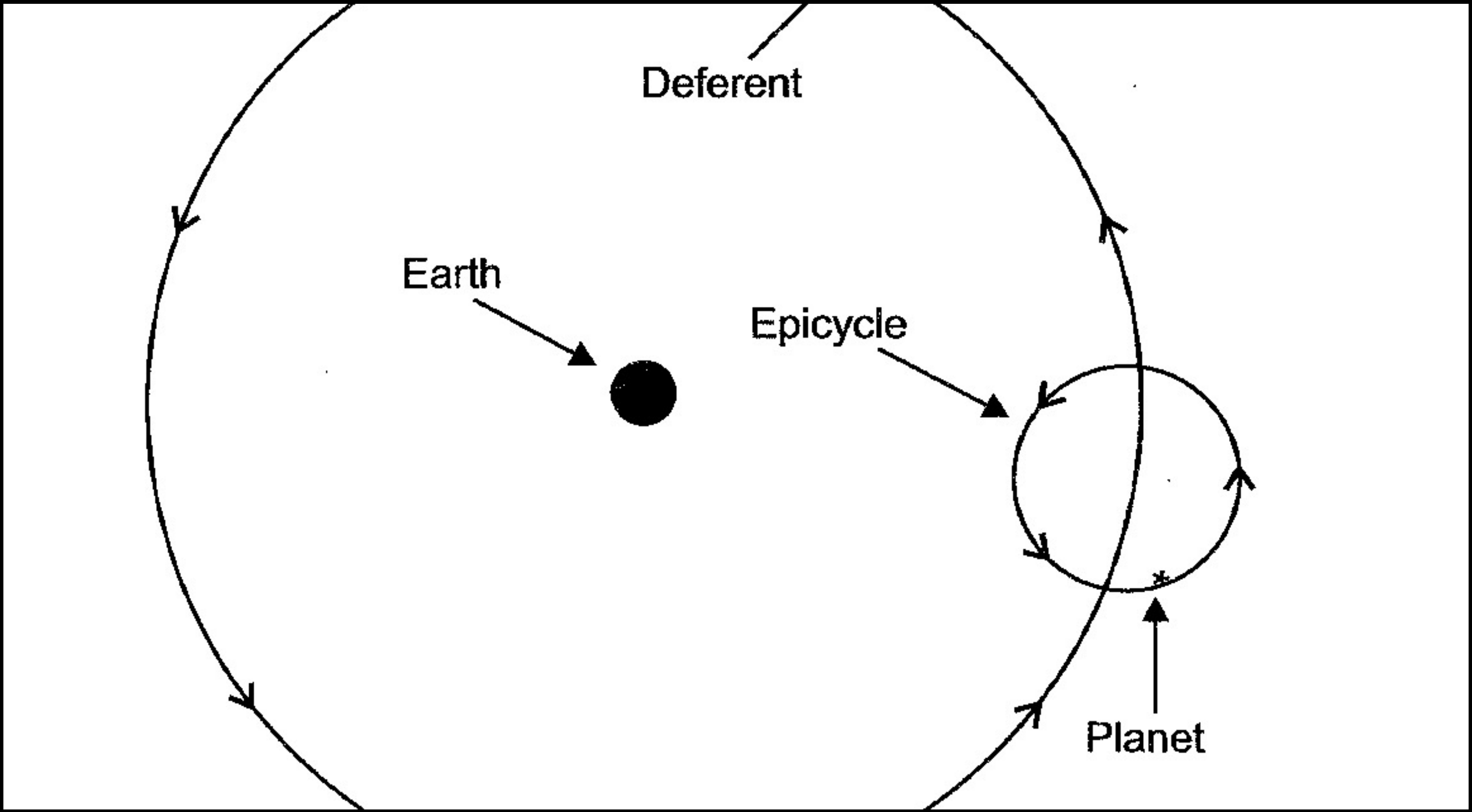
Ptolemy's Model – the carousel



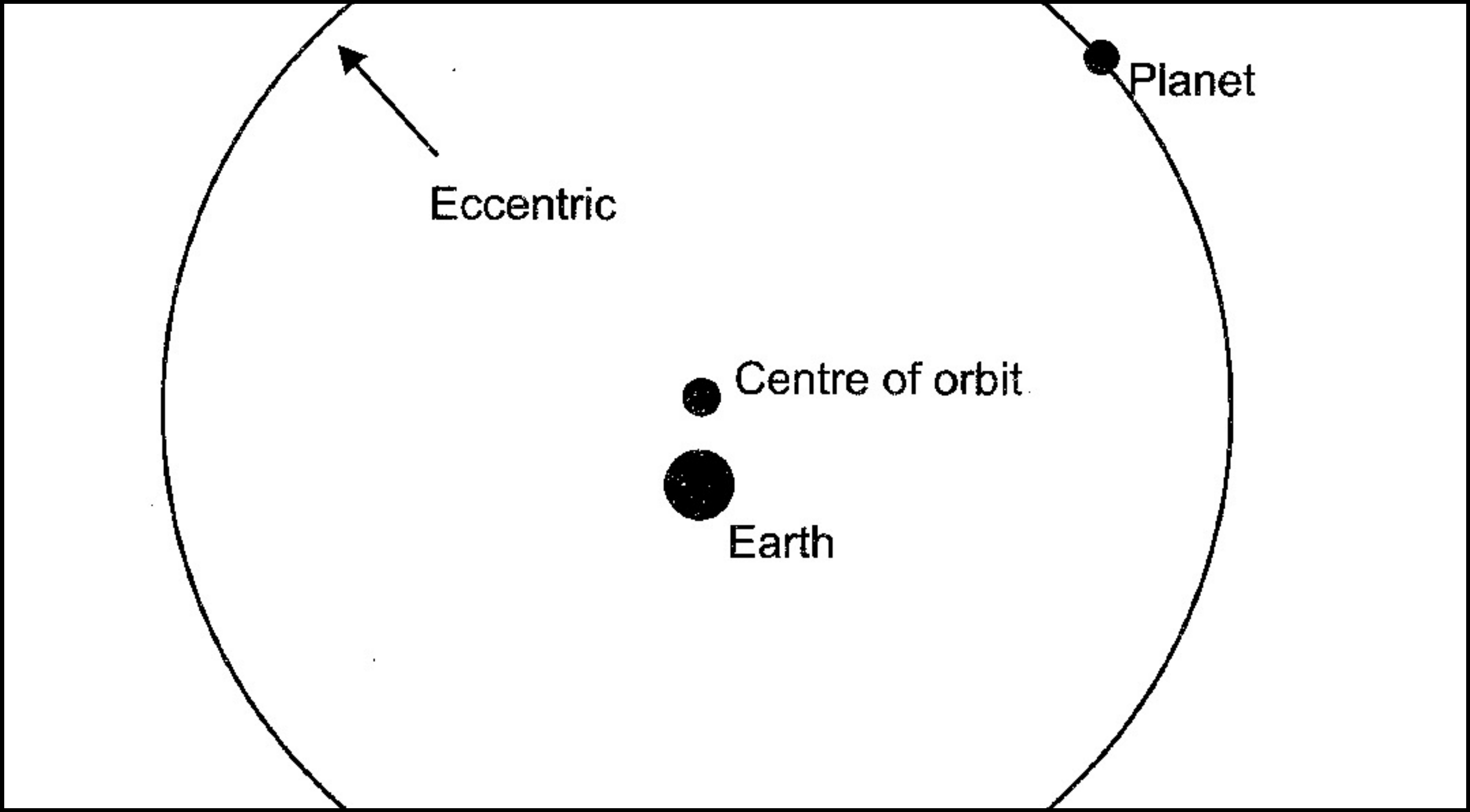
Ptolemy’s Model – Planetary Motion



Ptolemy's Model – the components

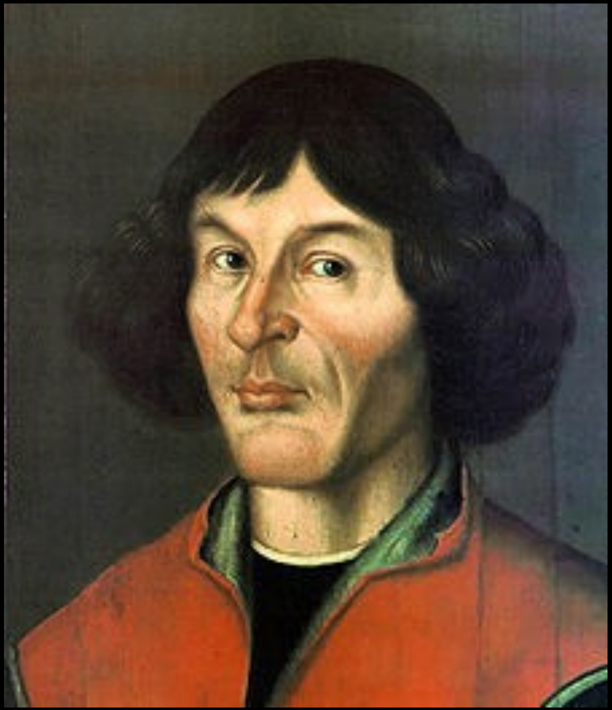


Ptolemy's Model – the eccentric



The Ptolemaic model lasted for 1400 years

The Birth of Modern Science

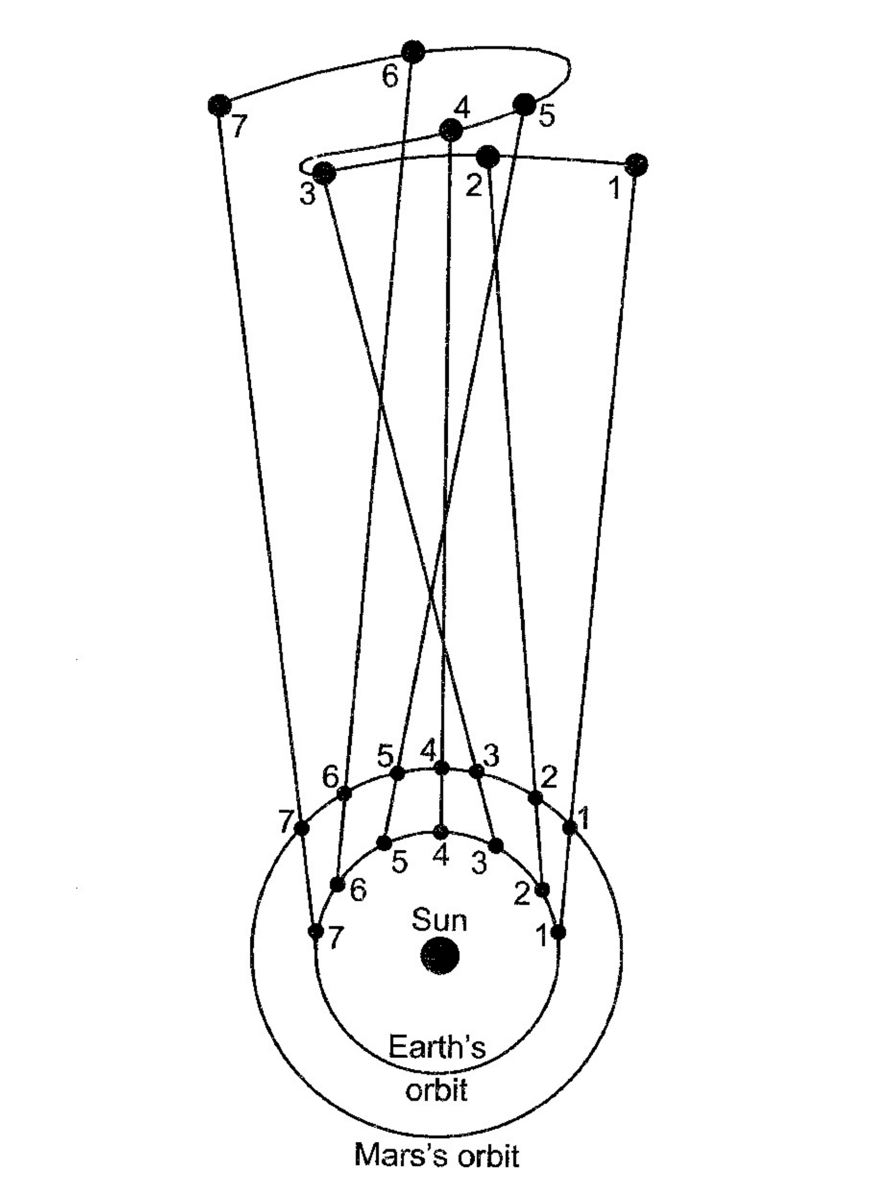


Nicolaus Copernicus (1473 -1543)

The Copernican Revolution

- The Sun at the centre
- Thus the Heliocentric System
- The planets moving in concentric circles around the sun
- The Moon moving in a circle around the Earth once a month
- The Earth rotates on its axis once a day

Copernican Retrogression



Objections to the Copernican System

- Not a good fit with observations
- No strong wind
- Stones dropped from the tops of towers landed at the bottom
- No phases of Venus
- The stars showed no parallax
- It was contrary to scripture

Copernican Supporters

- Tycho Brahe (1546 – 1601) Danish astronomer

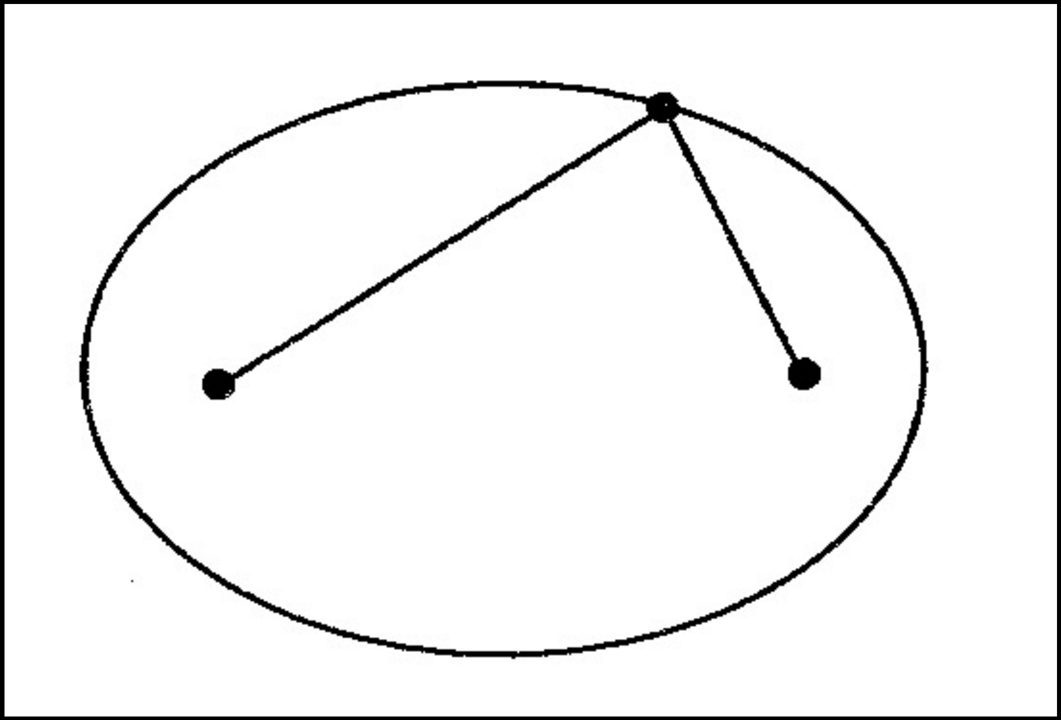
- He moved to Prague (1597) and took on

- Johannes Kepler (1571 – 1630) as his assistant

Brahe was jealous of young Kepler

- So he gave him the problem of Mars
- Kepler was forced finally to the realization that the orbits of the planets were not cir*cles* as demanded by Aristotle and assumed implicitly by Copernicus, but were instead the "flattened circles“
- ie. *ellipses*

The Ellipse



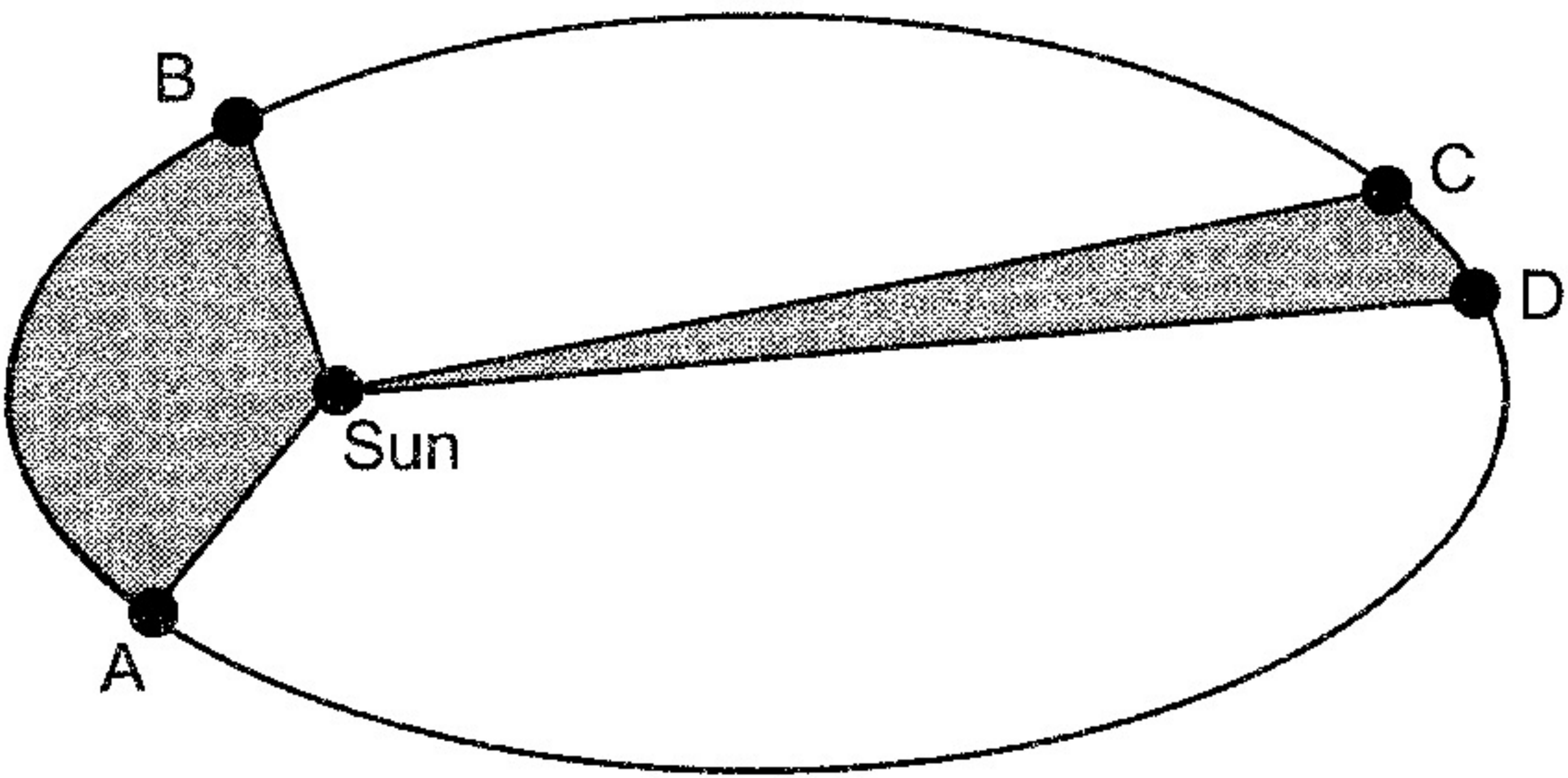
Kepler’ s Laws

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

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

- The ratio of the squares of the revolutionary periods for two planets is equal to the ratio of the cubes of their semimajor axes.

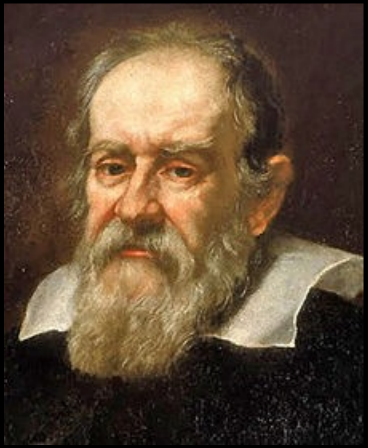
Kepler’s Laws



The Attitude of the Church

- Copernicus delayed publication until on his death bed - 1543
- Giordano Bruno - burned at the stake - 1600
- Kepler kept his head down   d. 1630
- Galileo Galilei (1564 - 1642) could not resist teasing his tormentors

The Father of Modern Science



Galileo Galilei (1564 - 1642)

Galileo Galilei (1564 - 1642)

Built telescopes which showed:

- The four large moons of Jupiter
- Craters on the surface of the Moon
- The phases of Venus
- Also established the laws of mechanics

Jupiter with moons

Galileo Galilei (1564 - 1642)

Offered a solution to the Longitude Problem:

- Jupiter's moon Io
- Period of 42 hrs 27.5 minutes
- Galileo produced tables
- Worked on land but not on ships

The Astronomical Unit (AU)

The distance between the Earth and the Sun

Kepler's Third Law:

The ratio of the squares of the revolutionary periods for two planets is equal to the ratio of the cubes of their semimajor axes

The Astronomical Unit (AU)

The ratio of the squares of the revolutionary periods for two planets is equal to the ratio of the cubes of their semimajor axes

Period	Relative Distance
Earth 1.000	1.000 AU, by definition
Mars 1.880	
Therefore	1.523 AU

The Astronomical Unit (AU)

The distance between the Earth and the Sun

Giovanni Cassini (1625 – 1712) measured the AU to be at 140 million kilometres (87 million miles)

How?

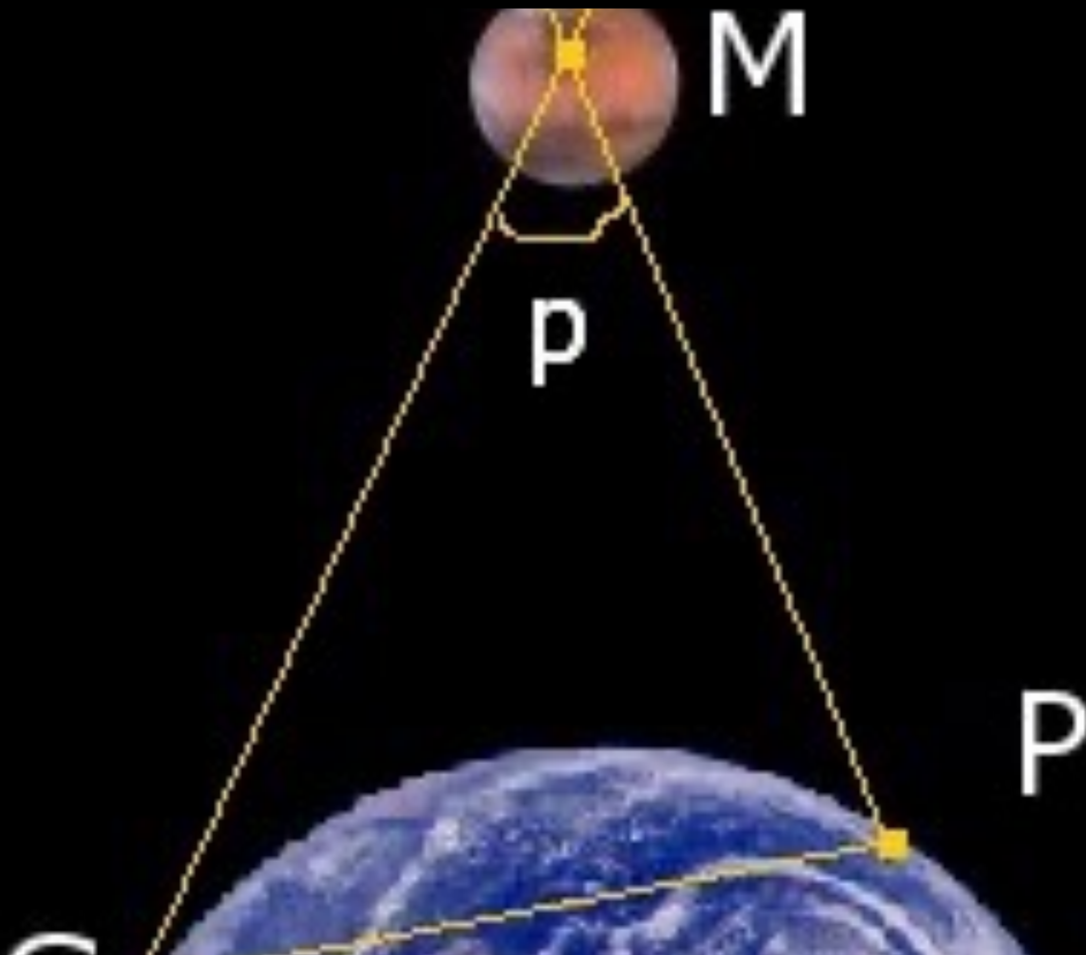
The distance to Mars

- The measurements were carried out at the moment when Mars and the Sun were in *opposition* – on opposite sides of the earth.

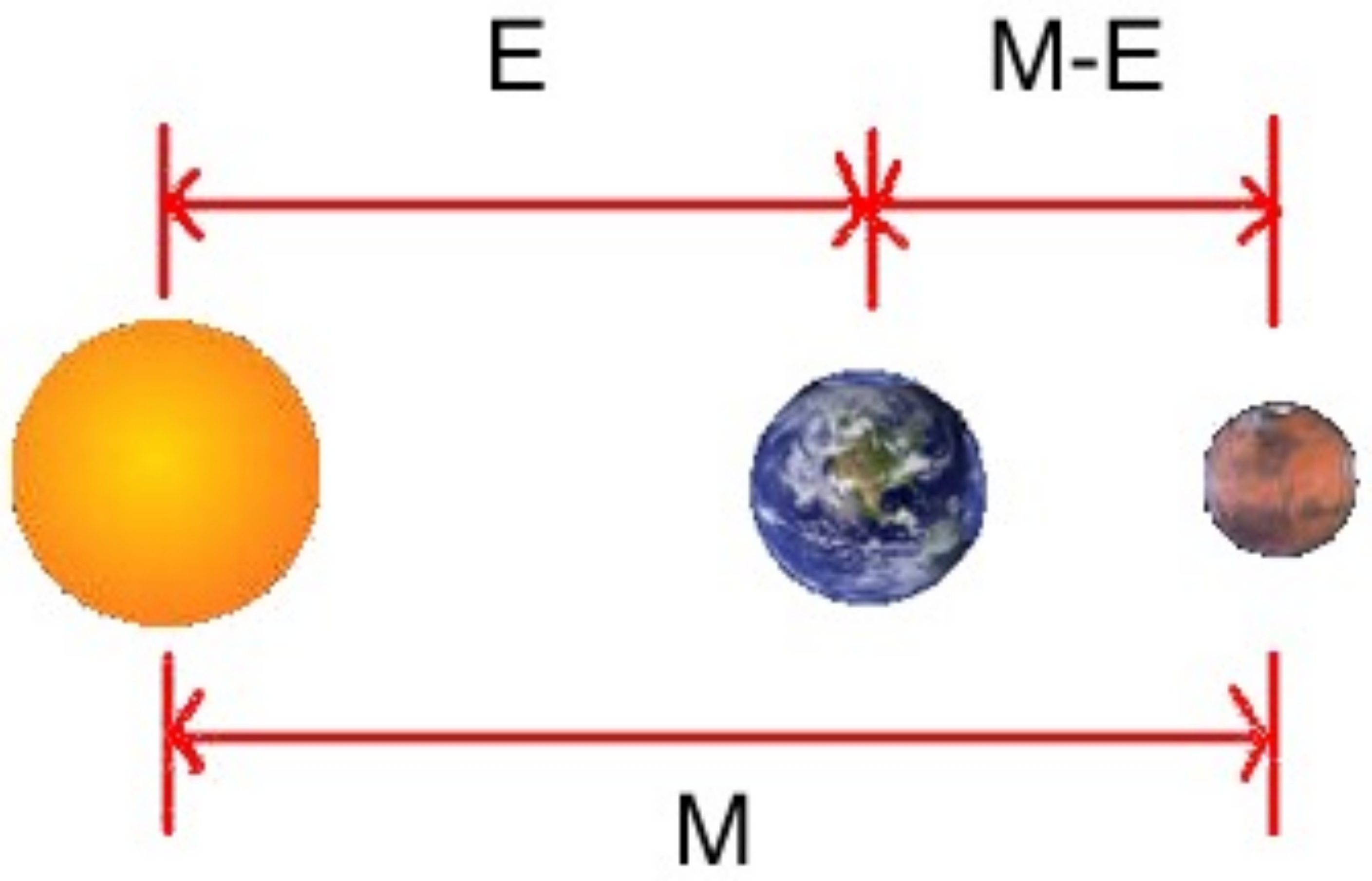
- Mars was triangulated from two places simultaneously: French Guyana and Paris

- Bye the way, the opposite to *opposition* is *conjunction*

Guyana Paris



Sun Earth Mars



$$
\begin{aligned}
73{,}000{,}000 \text{ km} &= M - E \\
&= 1.524 \text{ AU} - 1.0 \text{ AU} \\
&= 0.524 \text{ AU}
\end{aligned}
$$

or,

$$
\begin{aligned}
1.0 \text{ AU} &= 73{,}000{,}000/0.524 \text{ km} \\
&= 139{,}312{,}977 \text{ km} \\
&\approx 140{,}000{,}000 \text{ km (87 million miles)}
\end{aligned}
$$

The Astronomical Unit (AU)

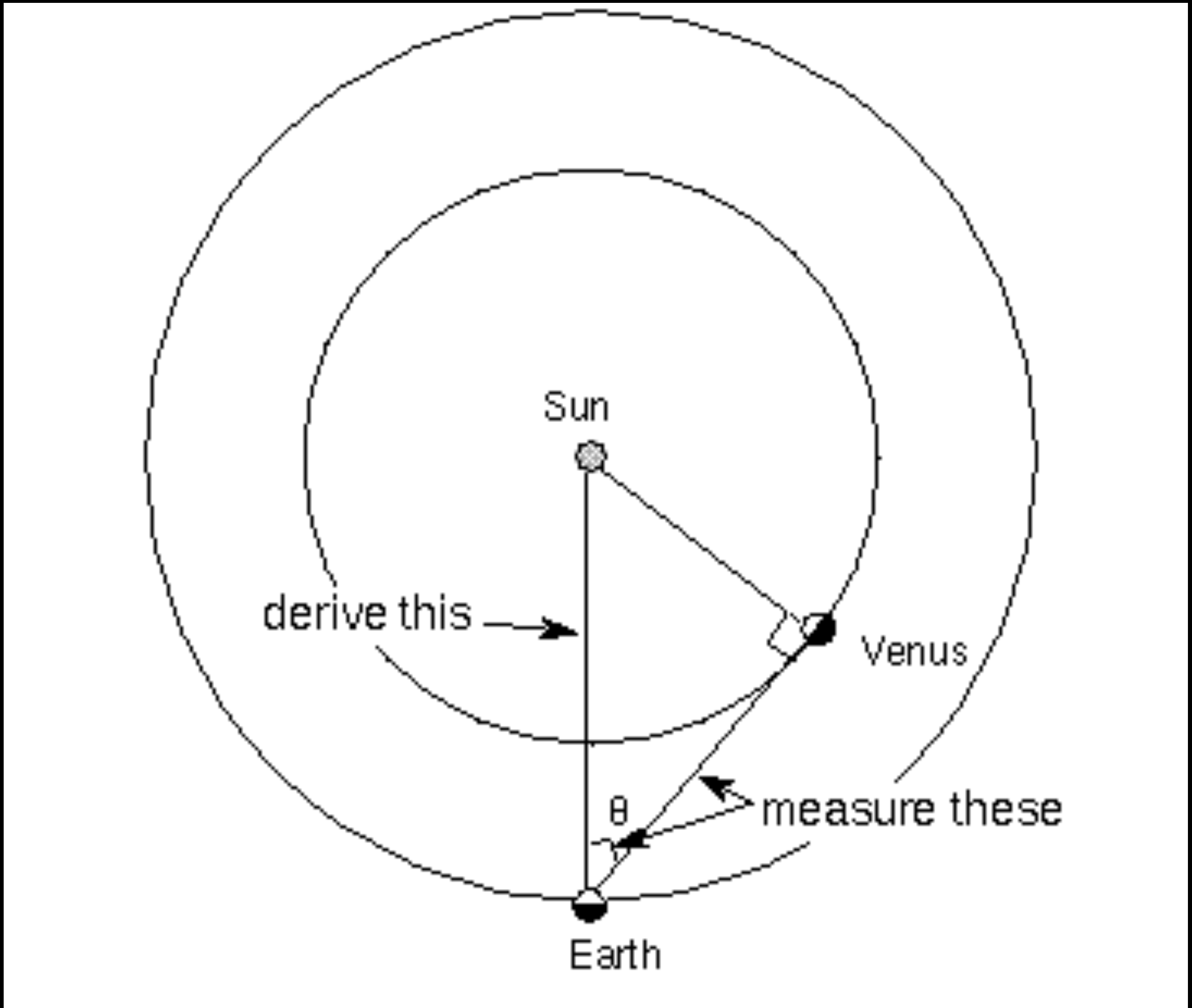
Edmond Halley (1656 – 1742) suggested a more accurate determination might be achieved using the transits of Venus

The Transit of Venus

Transits of Venus

1761	1769	153 million kilometres
1874	1882	149.59 million kilometres
2004	2012	(I saw them both!)
2117	2125	

Radar Measurements (AU)



The Astronomical Unit (AU)

The distance between the Earth and the Sun

149,597,892 kilometres

(92,955,820.5 miles)

The Distance to the Stars

- True and Apparent Luminosity

- If all stars had the same luminosity then the brightest stars would be the nearest stars

- We can measure the *apparent* luminosity

- IF we know the distance we can then calculate the *absolute* luminosity

The Distance to the Stars

Friedrich Bessel (1784 – 1846) measured (1838) the distance to 61 Cygni

11.2 light years (6,000,000 AU)

Parallax angle = 0.3 arcseconds

1 arcsecond = finger width at 1.5 Km

The Parallax Method

The “base line” has recently been extended by the ESA Gaia satellite.

Gaia is at the Lagrange point L2 of the Sun Earth system

Notwithstanding the parallax method has a limit of approximately 400 light yeas

The Milky Way has a diameter of 100,000 light years

Our Solar System is some 26,000 light years from the galactic centre

The angle between the plane of the solar system and the galactic plane is approx. 60 degrees.

Thus the Parallax method only works for a tiny proportion of the starts in the Milky Way

The Distance to the Stars

However this is a tiny proportion of a huge number

Approximately 100 Billion

So we still can measure the distance to a lot of stars!

AND

There is a correlation between the spectral characteristics of a star and its absolute luminosity

Henrietta Swan Leavitt
(1868 – 1921)

The Small Magellanic Cloud

Found 25 variable stars – all at the same distance!

She noticed that their *period* correlated with the maximum *brightness*

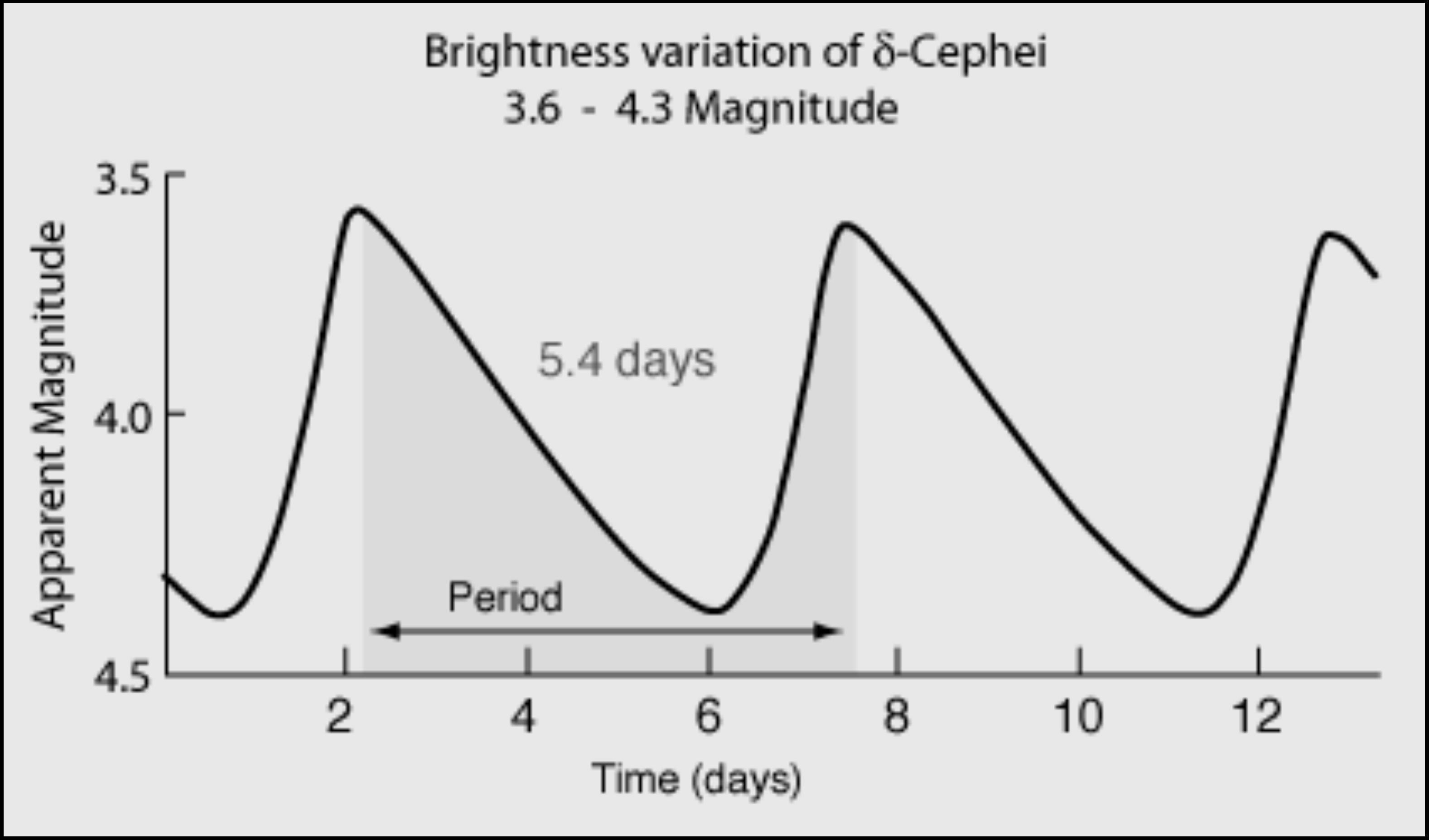
She gave them the name Standard Candles

They are now known as Cepheid Variables

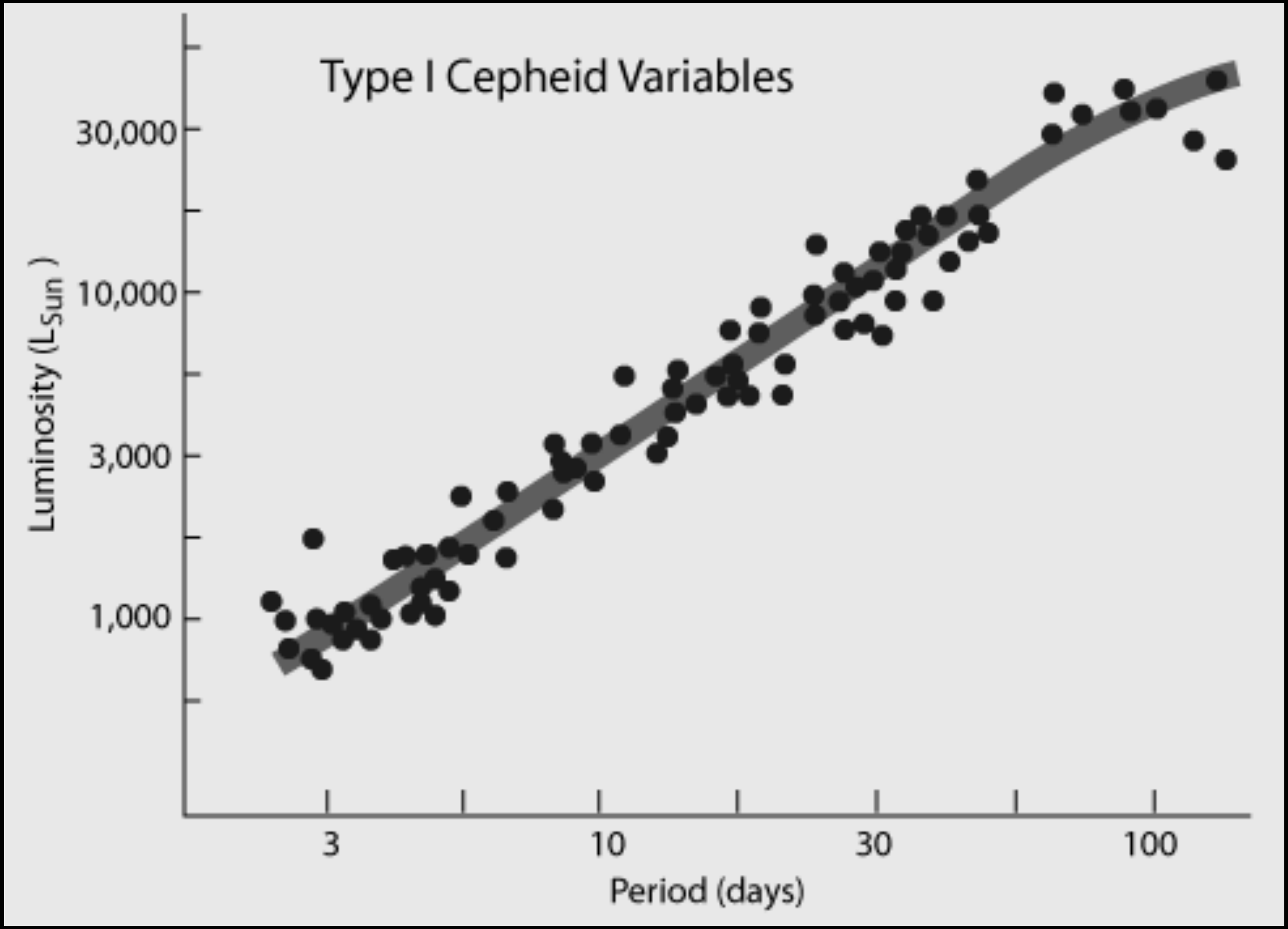
Cepheid Variables

- The term *Cepheid* originates from the first variable star of this type to be identified:
- Delta Cephei in the constellation Cepheus, identified by John Goodricke (1764 – 1786) in 1784
- Goodricke studied the variable star Algol a variable star of a very different type.

Cepheid Variables



Period-luminosity relationship



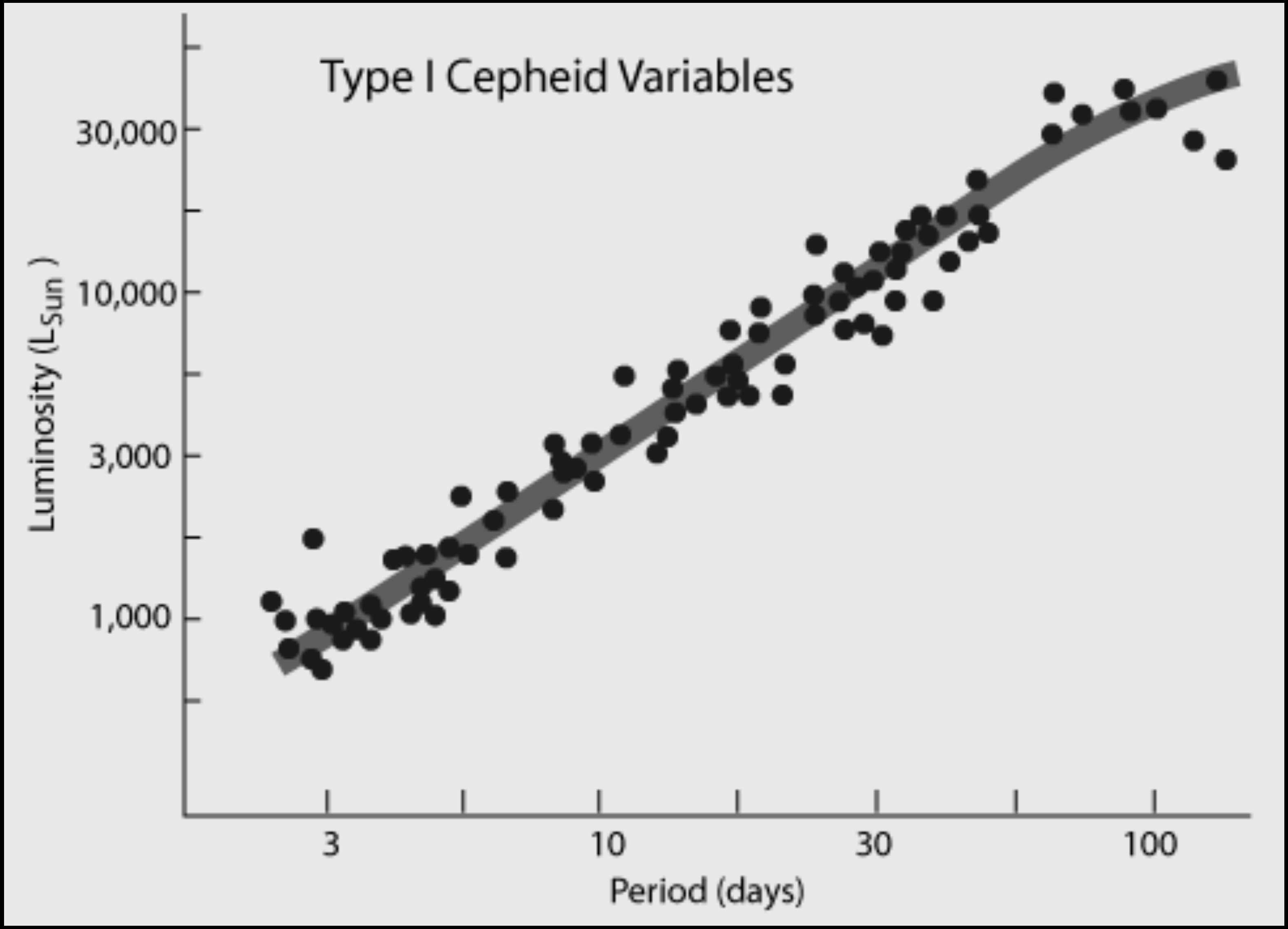
Cepheid Variables

The search was on for a Cepheid Variable at a known distance (parallax)

From the *Apparent* luminosity one could then calculate the *Absolute* luminosity

One could then calibrated the Period - Luminosity curve

Period-luminosity relationship



Cepheid Variables

Armed with this one could:

Find any Cepheid Variable

Measure its Period

Look up its Absolute Luminosity from the graph.

Measure its Apparent Luminosity at maximum

Use the difference in the luminosities to calculate its distance

The Small Magellanic Cloud

But how did Ms Swan Leavitt see the Magellanic Clouds from Harvard?

I didn’t know, so I asked Brian Schmidt!

She studied photographic plates sent from

Boyden station

Harvard College Observatory
Boyden Station
Arequipa, Peru 1889–1927

Henrietta Swan Leavitt
(1868 – 1921)

Died at the age of 53

She never saw the
subject of her fame.

Small Magellanic Cloud   199,000 Light years

Edwin Powell Hubble (1889 – 1953)

Edwin Hubble

Found Cepheid variables in distant galaxies

Was thereby able to measure the distance to the galaxies

1 Light-year = 9,460,730,472,581 km

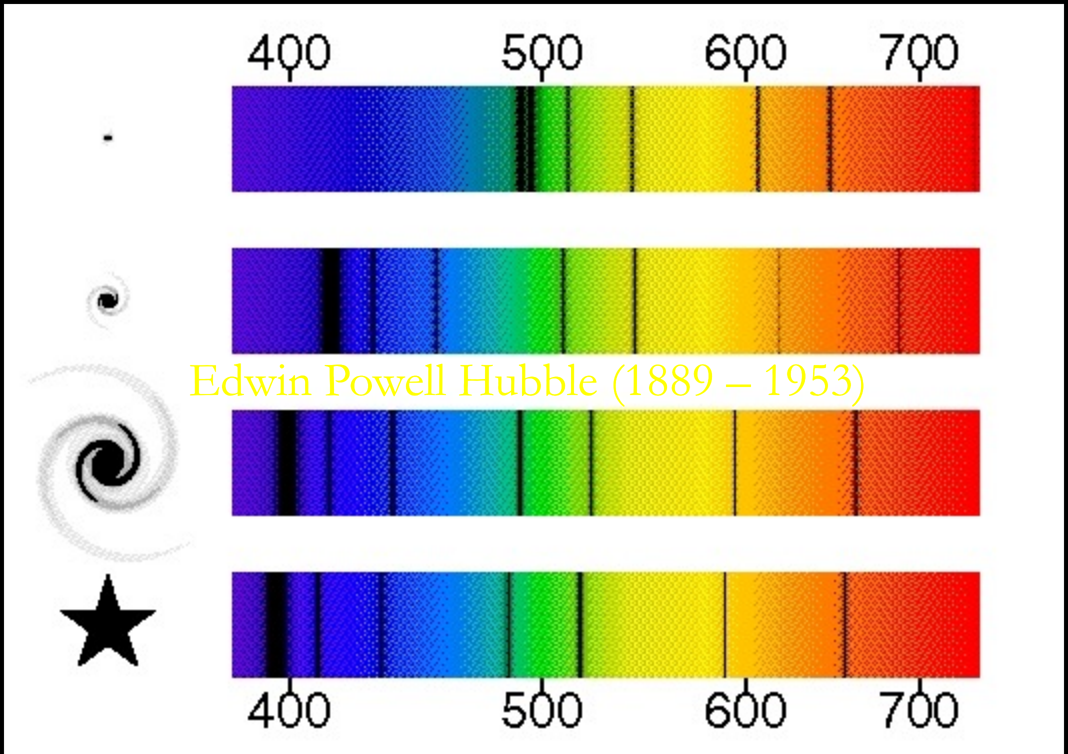
Small Magellanic Cloud

210,000 Light Years

Andromeda Galaxy

2.5 Million Light Years

Red Shift



Edwin Hubble

Discovered a relationship between the DISTANCE to the galaxy and its RED SHIFT (ie. its recessional velocity)

Hubble's Law $V = H \times D$

One could then measure the Red Shift

Calculate the Recession Velocity

Use Hubble's Law to obtain the Distance

Edwin Hubble

One can also use Hubble's Constant to work out the age of the Universe

The age of the Universe

2 minute Film

Other Standard Candles

Planetary Nebula Luminosity Function

Tully-Fisher Relation

Type Ia Supernovae

Sunyaev-Zeldovich Effect

Gravitationally Lensed Quasars

Cecilia Helena Payne-Gaposchkin
(1900 – 1979)

Cecilia Helena Payne-Gaposchkin

Born in England

Moved to the USA

In her 1925 PhD thesis she showed that stars were predominantly composed of Hydrogen. This contradicted the accepted view. Her supervisor, Henry Norris Russell, persuaded her not to publish

By 1929 Russell had reached the same conclusion and published

Payne was appointed to the Chair of the Department of Astronomy, and became the first woman to head a department at Harvard

So how big is the Universe?

It might be infinite

But we can ask

How big is the *Known* Universe

How big is the Universe

10 min Film

Twinkle, twinkle little star,

Now we're learning what you are.

For by spectroscopic ken,

You're Helium and Hydrogen.

Twinkle, twinkle little star,

How I've wondered what WE are.

Now I know you're made of dust

Now I know you're just like us.

Twinkle, Twinkle oh so far,

Now I know I am a star.

And now for something *almost* completely different....

The Galaxy

4 minute Film

The End