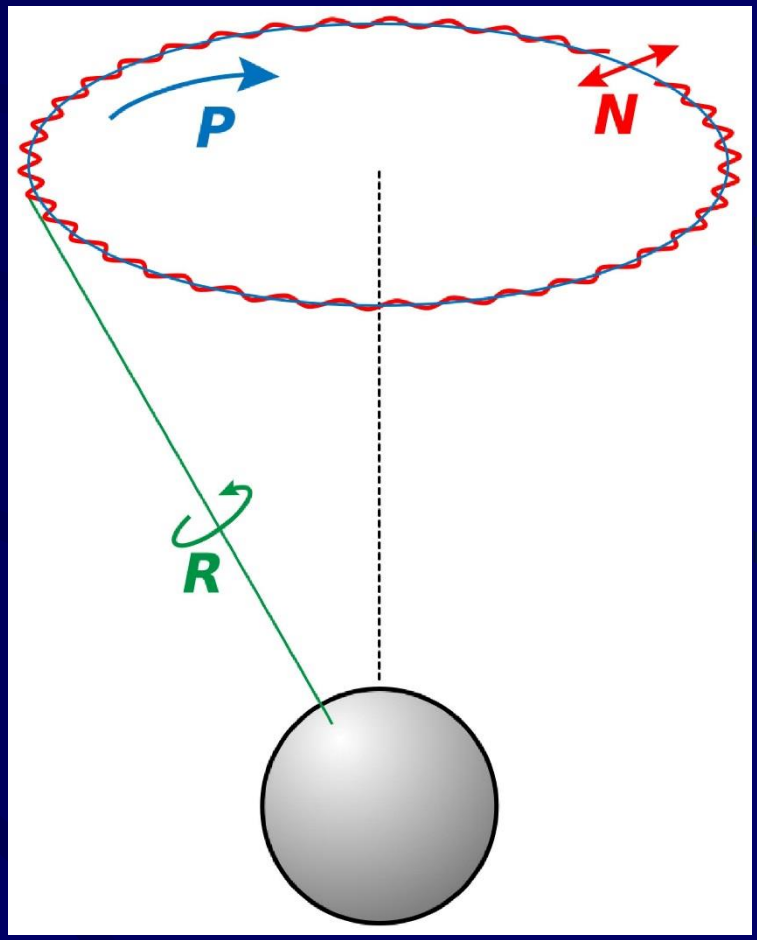
The Scale of the Cosmos

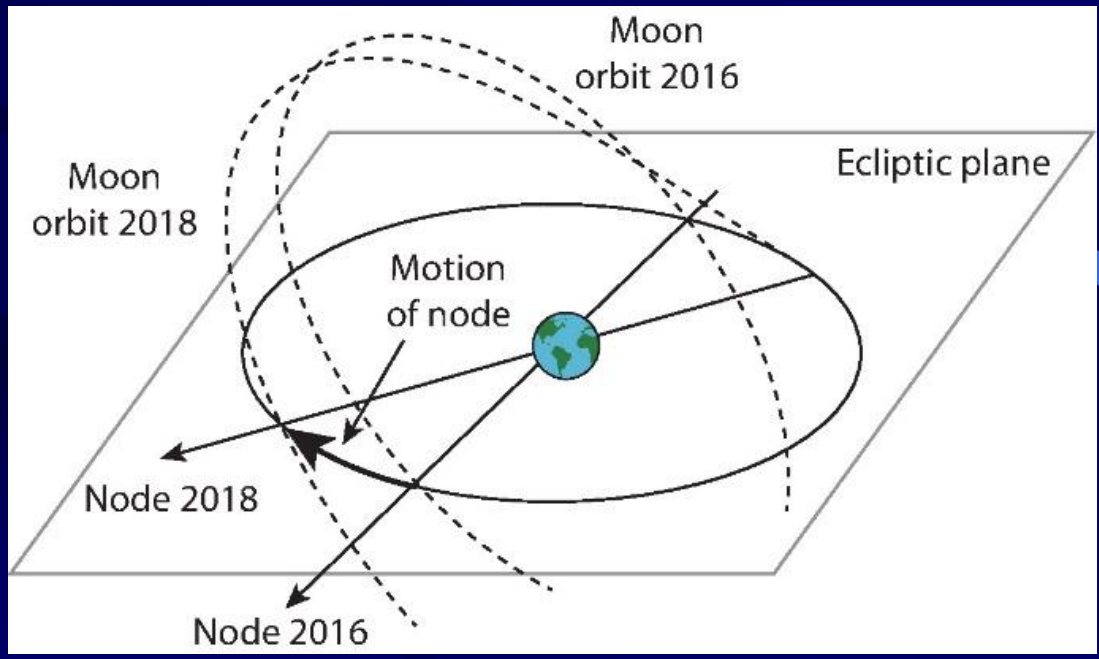
Physical Astronomy: The Earth behaves like a spinning top!

- Euler: So we can describe it with the spinning-top-equations of physics
- Rotates around axis, axis rotates around pole of the ecliptic
- It “nods” nutation



Motion of the moon's orbit is the cause for nutation

- Nutation happens on a 18.6 year cycle
- Node of moon's orbit rotates in 18.6 years
- You connect the dots…



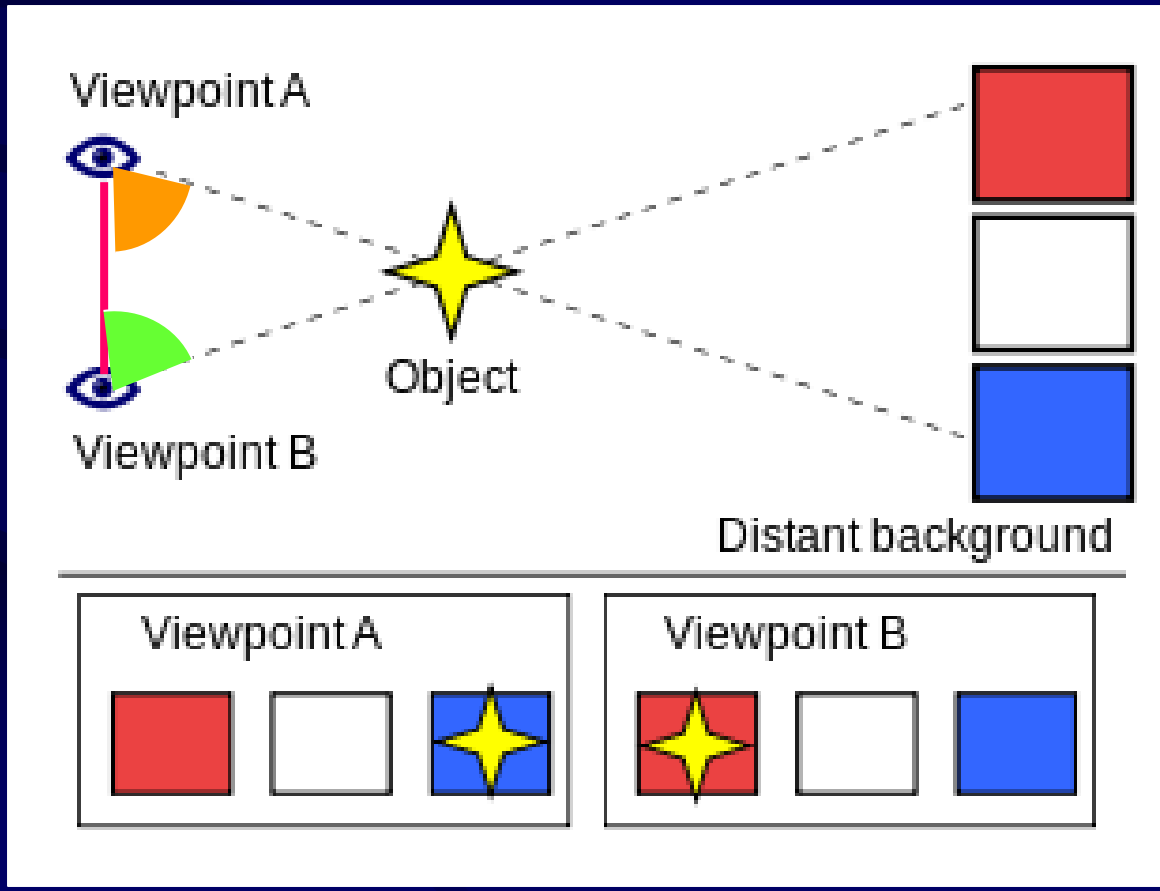
Scaling up the Physical Universe

- Need to measure the “constants” in Newton’s equations
  - Gravitational constant G
  - Mass of the earth and sun
  - Distance to moon
  - Distance to sun (AU)
- Radius of the Earth is known (Eratosthenes), so we can use Earth as a baseline

The Parallactic Effect Can Be Used to Measure Distances

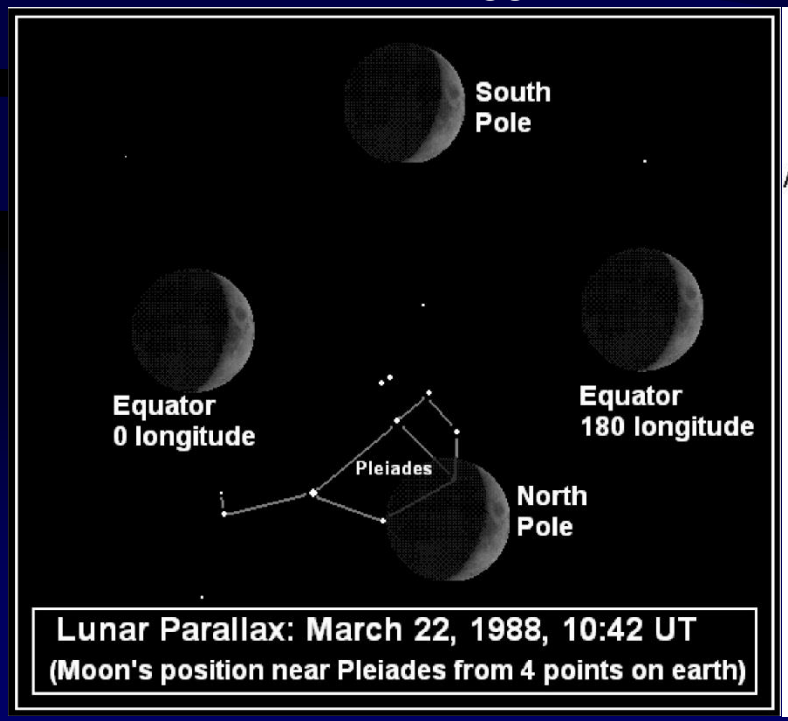
- Demo: look at you thumb with one eye closed

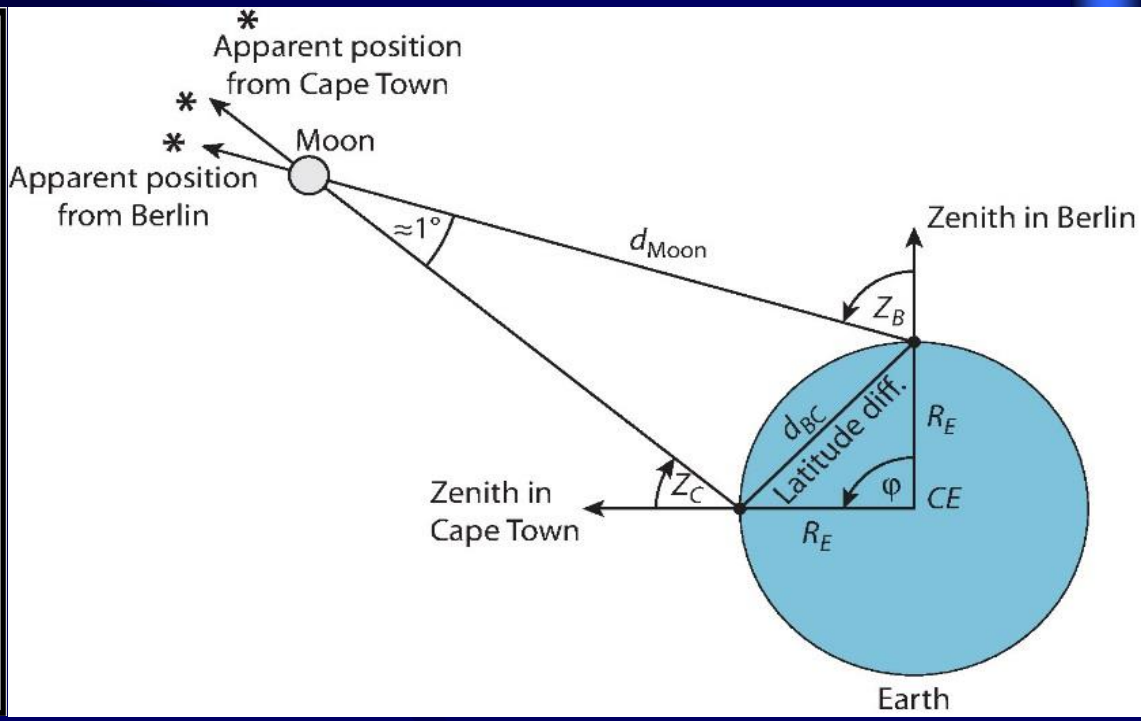
- Measure the baseline (distance A to B)
- Measure angle at B
- Measure angle at A
- Use geometry of triangles to determine distance to object:
  - If two angles plus one side of a triangle are known, everything else can be computed



Distance to the Moon by Parallax

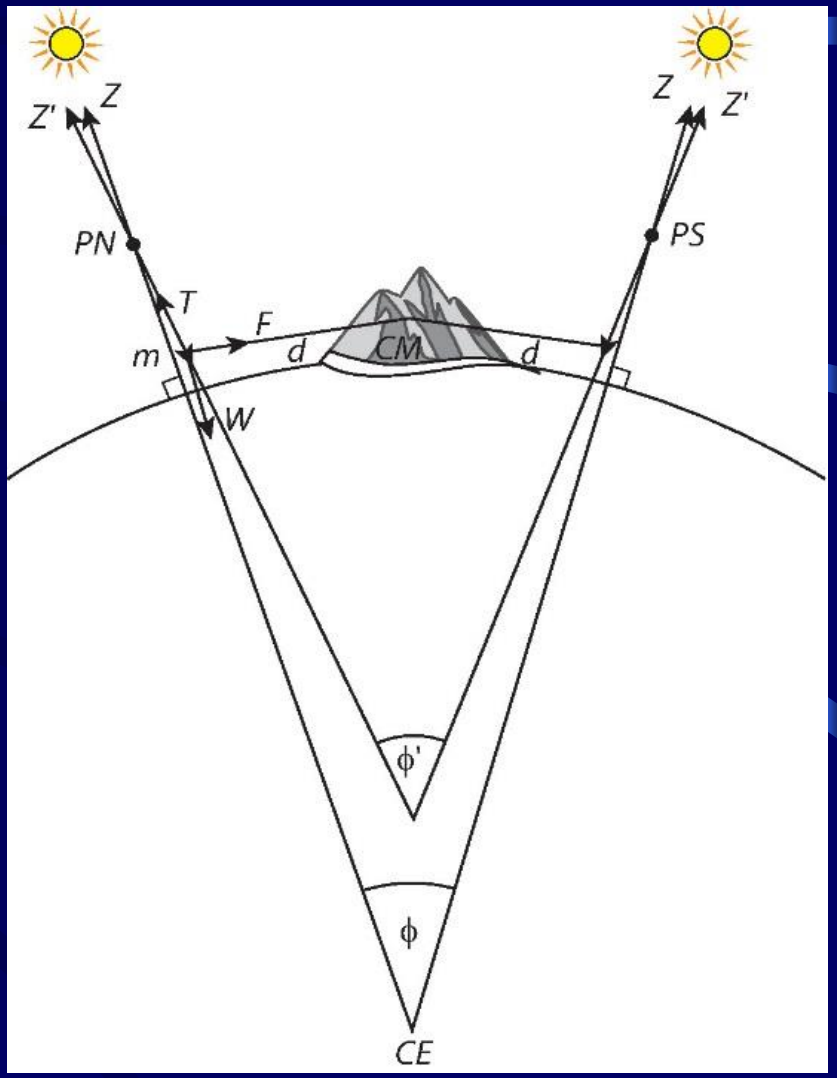
- Lacaille and Lalande measure simultaneously from Berlin and Cape Town
  - On August 31, 1752: $Z_B = 33.11°$; $Z_C = 55.14°$
- Parallax 1º and known baseline $d_{BC} = 8{,}650\text{km}$ yield $d_{Moon} = 384{,}000\text{km}$





Maskelyne "Weighs" the Earth (1774)

- Schiehallion is an isolated mountain
- Measure Z by astronomy, Z' by pendulum
- Pendulum is attracted by mountain AND earth
- Can compute relative strength of force of mountain and earth
- Discrepancy ZZ' gives away mass of the earth if mass of mountain is estimated



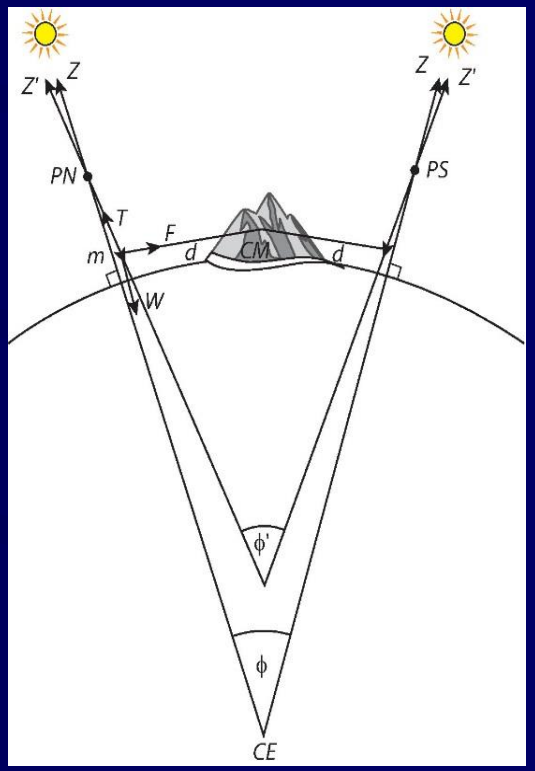
Maskelyne "Weighs" the Earth

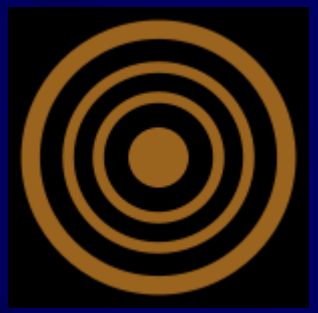
- Mass of mountain is estimated by measuring density of granite in lab, eyeballing volume of mountain
- Granite is 2.75x denser than water, the earth is 5.5x denser!

➔The earth is not hollow

➔It must be much denser inside

- $M_{Earth} = 5.97 \times 10^{24}$ kg





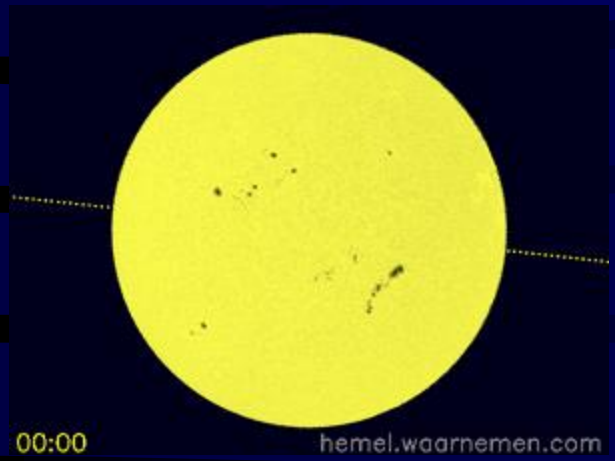
Halley's hollow earth hypothesis to explain anomalous magnetic readings

Measuring the Astronomical Unit

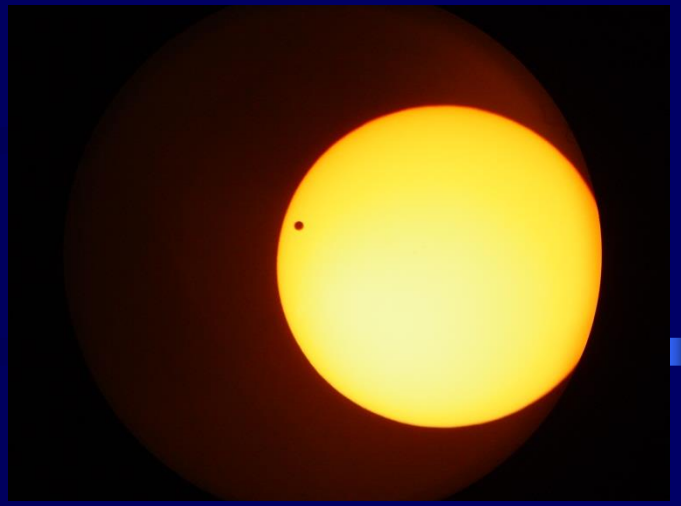
- Kepler's Law III only gives relative distances
- Need to observe an event in the solar system from two different locations to triangulate the distance
- Halley(1716): Venus transits should work!
- Problem: they only occur once in 100 years

Why doesn't Kepler III determine the A.U.?

- Kepler's third law is only able to settle the relative, not absolute, distances in the solar system
- $a^3 / P^2 = 1$ if a is measured in AU and P in Earth years
- Example: from measuring the Jupiter year to be 11.8 years, we deduce $a_{Jupiter} = 11.8^{2/3} = 5.2$ AU, i.e. Jupiter is about 5 times farther from the Sun than the Earth – but how far?

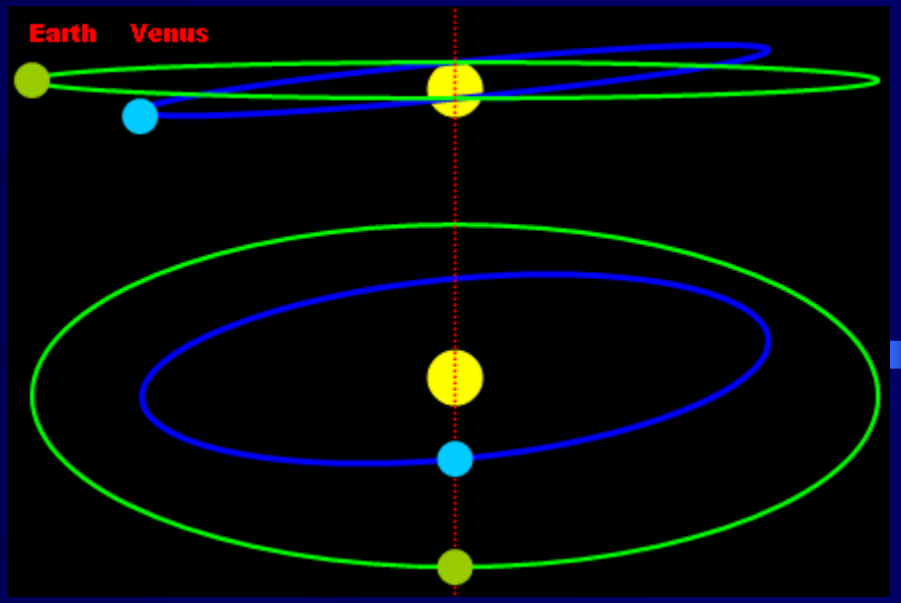


Venus Transits



- Basically an eclipse of the Sun: Venus stands between Earth and Sun
- They are rare: a pair 8 years apart every 121.5 and 110.5 years apart
  - 13 Venus years are roughly 8 Earth years
  - 395 Venus years are very close to 243 Earth years
- Same situation reoccurs after 243 years

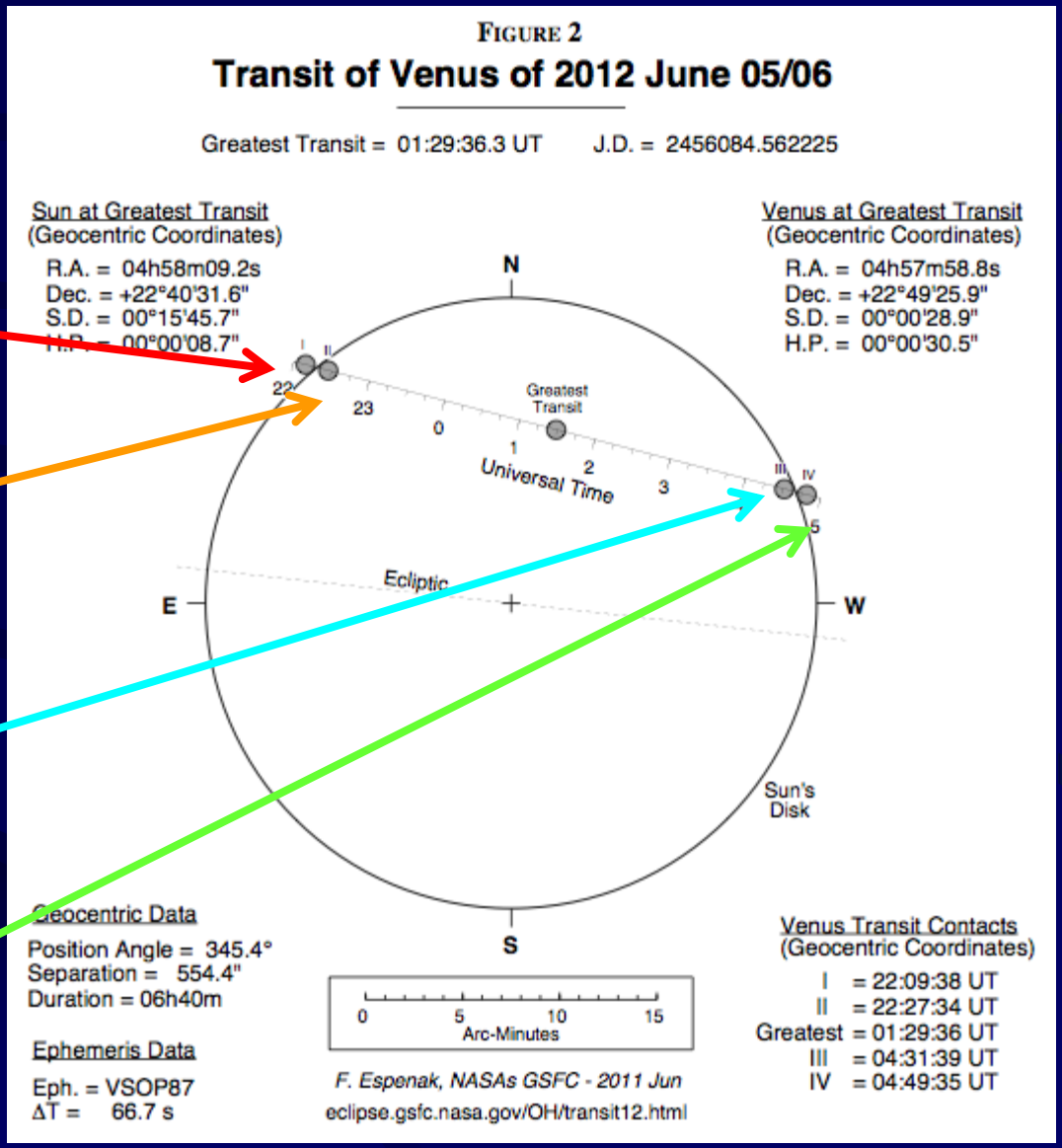
Why are they so rare?



- Venus orbit is inclined
  3.4 degrees w.r.t. Earth's orbit
- Usually Venus passes over or under the Sun
- Only when Venus is close to her orbital nodes (goes through the plane of Earth's orbit) can we observe it

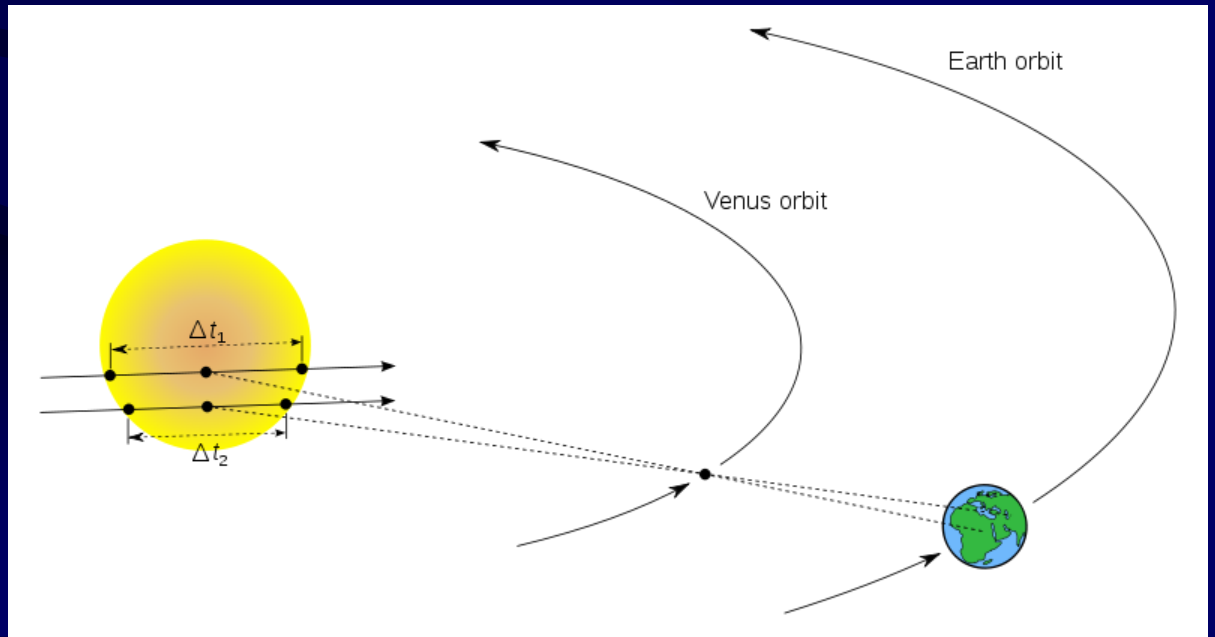
Transit Anatomy

- Contact I: Venus touches edge of Sun from outside
- Contact II: Venus touches edge of Sun from inside
- Contact III: Venus touches edge of Sun from inside
- Contact IV: Venus touches edge of Sun from outside

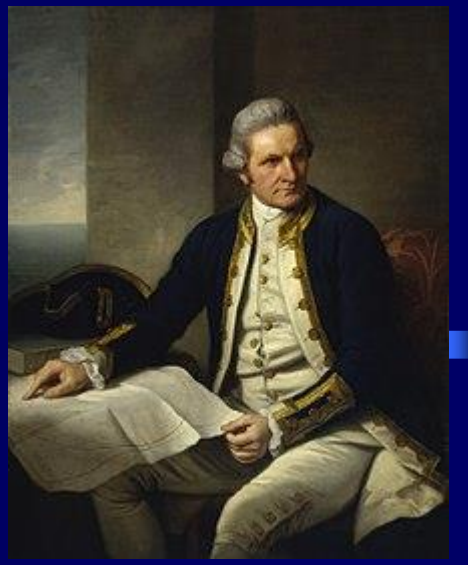


Scaling up the Solar System

- Early on the best way to measure the Astronomical Unit (A.U.), i.e. the distance between Earth and Sun
- Idea: project a known distance on Earth onto the Sun, deduce distance Venus-Earth
- Parallax!



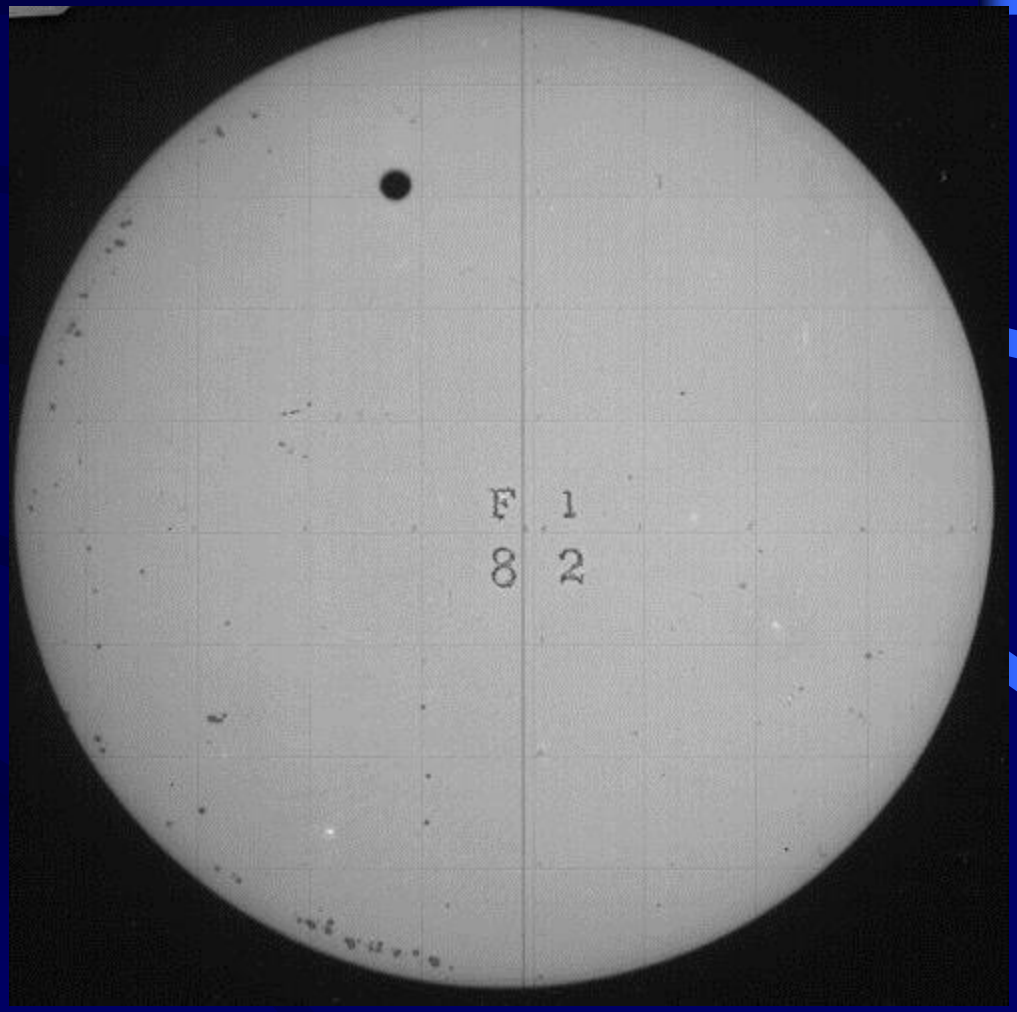
The 1761 & 1769 transits



- Captain Cook travels to Tahiti in 1769
  - Took the newly invented Marine Chronometer of Harrison with him for navigation (longitude!)
- Others observe from Baja California (span.!), South Africa, Siberia
- Value (derived by Lalande) is 1AU = 153 mill. km
- Problem: Black drop Effect hinders exact determination of entry/exit times

The 1874 & 1882 Transits

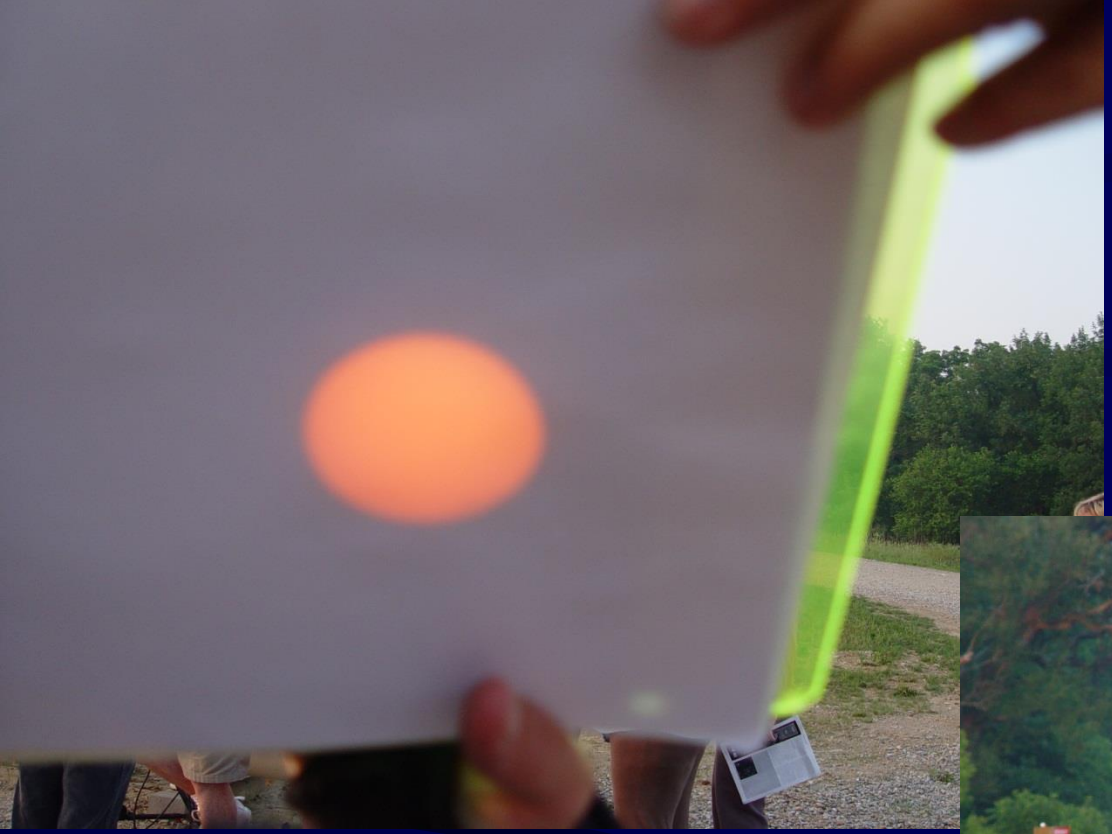
- The American astronomer Simon Newcomb combined the data from the last four transits, and he arrived at a value of about 149.59 million kilometers (±0.31 million km).
- Now: ±30m!



The Venus Transit of 2004

- June 8 at Prairie Oaks Metro Park

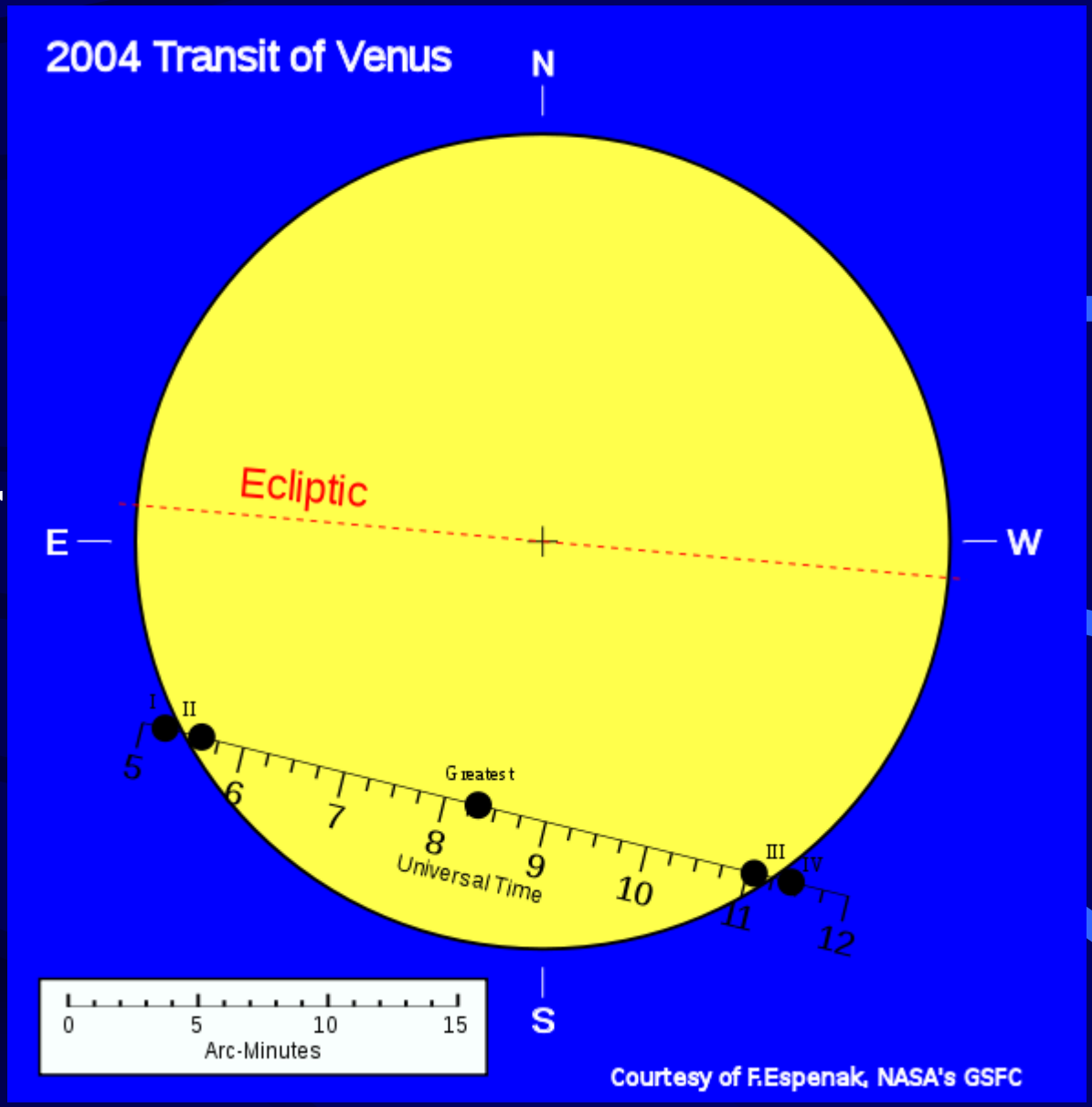
Observing Methods



- Projection on paper

- Solar filter

- EST = UT – 5 hr

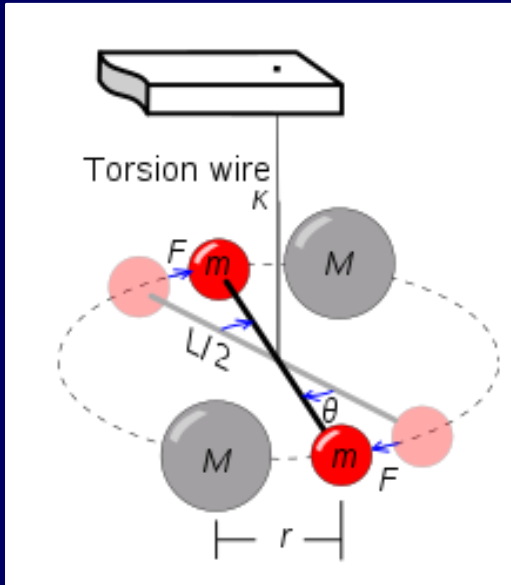

2004 Transit of Venus
N
E
W
S
Ecliptic
I
II
III
IV
Greatest
5
6
7
8
9
10
11
12
Universal Time
0
5
10
15
Arc-Minutes
Courtesy of F.Espenak, NASA's GSFC

Venus' Atmosphere and Black Drop Effect

G – Measuring the Strength of Gravity

- G is a very small constant, gravity is very weak!
- Cavendish succeeds in 1798 to measure the gravitational attraction between two lead balls (high density, i.e. mass !) with a torsion balance

- $G = 6.67 \times 10^{-11} N\ m^2\ kg^{-2}$



Now the masses of celestial objects can be readily computed!

- Example: sun's mass follows from the fact that the earth takes one sidereal year = 365.25636 days to travel a distance 2π AU = 300π million km = 942 million km
- Velocity of earth: v = d/t = 2.58 million km per day = $v_{Earth} = 30$ km/s
- Since $F = G\,mM/R^2$ and $F = ma = mv^2/R$ we can solve for M = $M_{Sun} = 1.99 \times 10^{30}$kg

The Birth of Chemistry Dissolves Aristotle's Elements

- Chemistry and Thermodynamics emerge around the middle of the 18th Century
- Temperature is not Heat!
  - Temperature is what you measure with a thermometer, heat is a form of energy "stored" in an amount of substance
- Temperature scales
  - Fahrenheit, Celsius, Kelvin

The Delayed Scientific Revolution: Chemistry

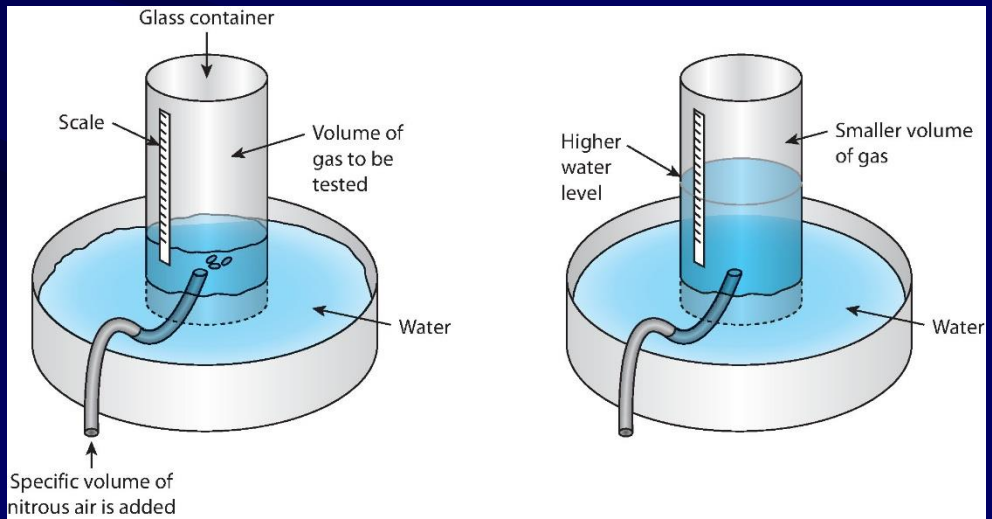
- Lavoisier's "*Methode de nomenclature de chimique*" (1787) appears 100 years after Newton's *Principia* (1687)
- In the 1770's Black, Lavoisier and Priestley discover that air is not an element, but consists of many "airs":
  - Oxygen, nitrogen, carbon dioxide
- Starting point: explain combustion process

From Phlogiston to Oxygen

- The epicycle theory of chemistry: phlogiston theory holds that a hypothetical substance (phlogiston) leaves the substance upon combustion
- Quite the opposite: oxygen enters the substance!

Priestley's "Good Air" Experiment

- Lavoisier claims that heating the calx of mercury (HgO) releases "good air" (normal air) using Priestley's good air test
- Priestley falsifies the theory by adding even more nitrous air (NO) and discovers oxygen



Lavoisier renames the Alchemistic Substances and starts Chemistry

- Lavoisier explains combustion: in an exothermic reaction (energy, heat released), substances combine with oxygen
- He names/labels the new elements for what they do (function)
  - Oxy-gen, i.e. generator of acids
  - Hydro-gen, i.e. water creator
  - Nitro-gen, i.e. soda creator
- This slick notation enables efficient work in chemistry, and really starts chemistry as a science

What became of Aristotle's Elements?

- Air → now a state of matter ("gaseous") or a mixture of gases (80% nitrogen, 20% oxygen)
- Water → a combination of two new elements (H_2O)
- Earth → a mixture of substances in their solid state
- Fire → the most enigmatic; eventually identified as heat or energy