The Modern Age

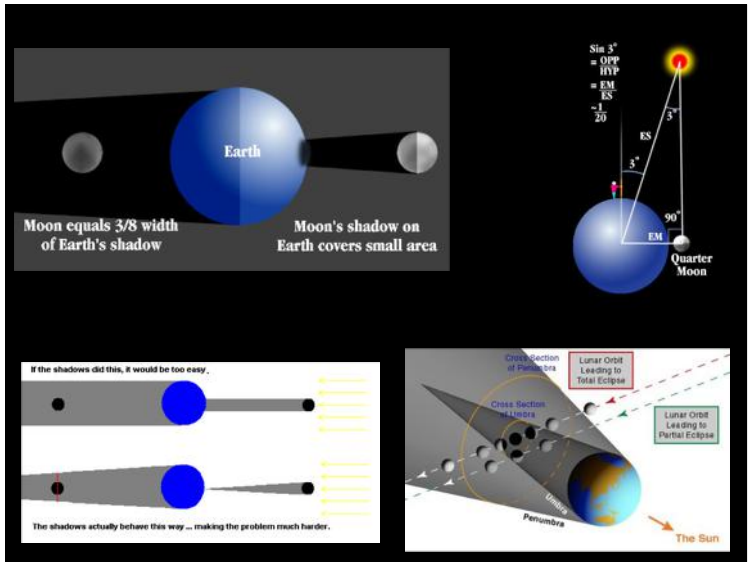
The Modern Age

*Q: What legacy did **Newton** leave?*

- ***Newton united*** the heavens & Earth
- ***same laws applied in both places***
- experiments "*here*" could tell us about "*out there*"
- ***scientific method*** became ***the*** tool for *deciding between competing ideas*
- result: *tremendous advances* in *technology*

Distance to the Moon

- ***Aristarchus*** (300 BCE)
- assume Earth's shadow at Moon ~ **2r** wide
- Moon travels through it in time **t = 2r/v**
- Moon also travels around Earth in **T = 2πR/v**
- equate **v**'s: **2r/t = 2πR/T** or **R/r = T/πt**
- if **T/t** ~ 30 d/3 h = 720/3 = 240, then **R/r** ~ 78
- correcting for conical shadow yields **R/r** ~ 60

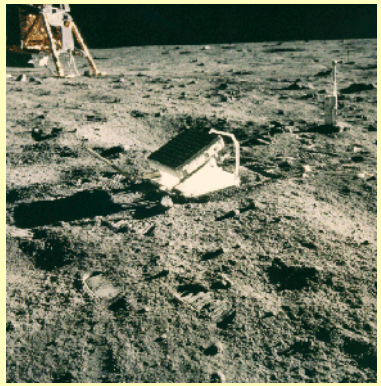


Distance to the Moon

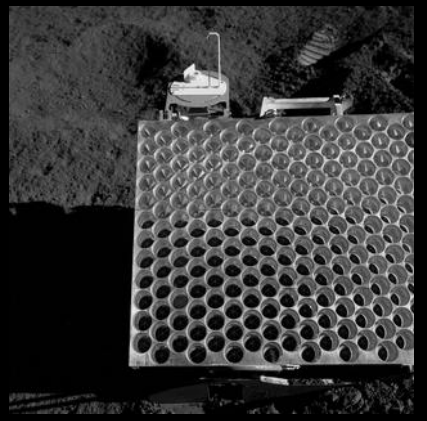
• ***Aristarchus*** (*~300 BCE*) estimated *lunar distance*

• today: ***laser-ranging*** yields ***60 Earth radii***
(eg) *shoot laser beam at reflectors left on Moon by* ***Apollo 11, 14 & 15*** *and measure* ***travel time***

• ***Moon*** is moving ***away from Earth ~ 4 cm/year***



Apollo 15 *(Appenines)*



• ***corner cube reflector (Lunar Ranging)***

Distance to the Sun

• ***Kepler*** found *distance from* ***Sun*** was related to *orbital period:* $P^2 = a^3$

• ***Kepler's "a" in AU*** ***(eg)*** *relative to the Earth-Sun distance*

• ***need the size of AU*** to find ***real*** distances!

• ***estimates*** of AU (at ***most***) a *few million km*

Planet	Dist. (AU)
Mercury	0.4
Venus	0.7
Earth	1.0
Mars	1.6
Jupiter	5.2
Saturn	9.6

Q: *How to determine the AU?*

• ***Edmund Halley*** had a "*cunning plan*" in **1716**

Transits of Venus

• every 1.6 years ***Venus*** is between ***Sun*** & ***Earth***

• *rarely*, alignment ***exact enough*** to ***transit*** *the* ***Sun***

• ***transits*** occur in *pairs*, ***8y apart every 100⁺ years***

Q: *Why so rare?*

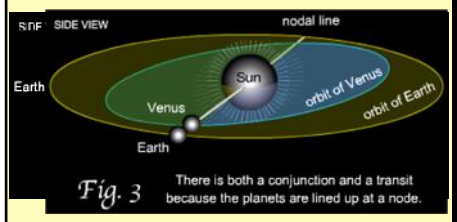


Fig. 3 There is both a conjunction and a transit because the planets are lined up at a node.

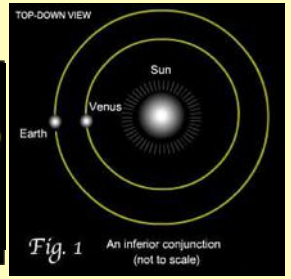
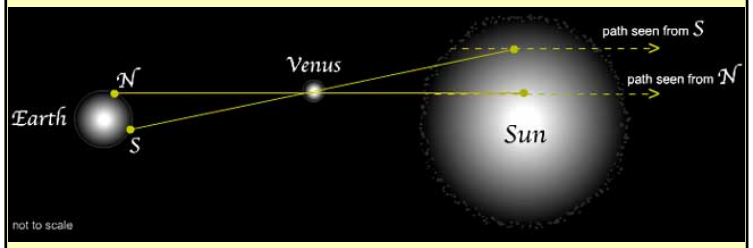


Fig. 1 An inferior conjunction (not to scale)

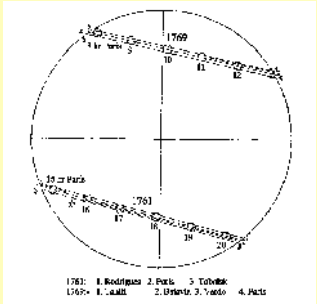
• by measuring *timing of transits on* ***Sun*** from *two or more* ***well-separated***, ***well-known*** *locations on Earth*, ***geometry*** yields *distance to* ***Sun***



• actual *mathematics* is ***involved*** (but *manageable*)

• ***1761/69 transits***: observers dispatched ***worldwide***
• ***Jeremiah Mason*** & ***Charles Dixon*** in ***S. Africa***
• ***Captain Cook*** in ***Tahiti***
• ***Guillaume Le Gentil*** in ***India*** (***"a few" problems)***

• timing was ***difficult***: *"black drop" effect*
• this ***significantly increased*** error in *final estimate*

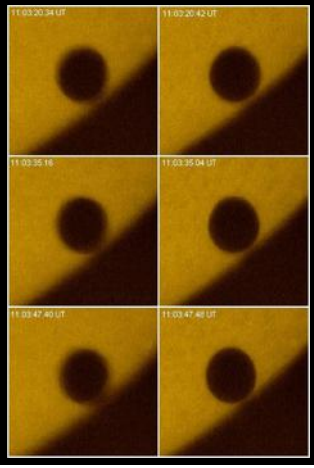


• combining data from ***1761/69 transits***, astronomers were able to ***estimate the AU***

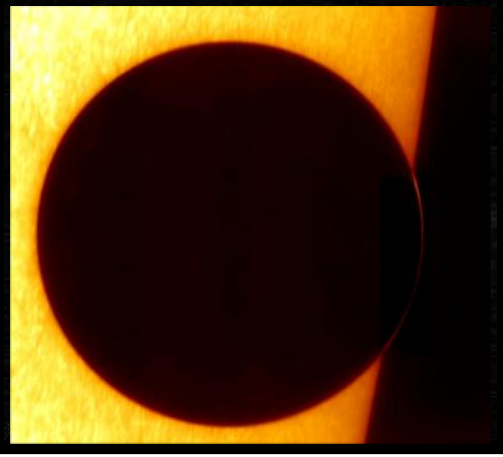
• ***Jospeh de Lalande, Thomas Hornsby,*** etc. calculated a distance of ***~153 million km***

• ***Simon Newcomb*** (1874 transit): ***~150 million km***

Black Drop Effect



Venus (*June 8, 2004*)

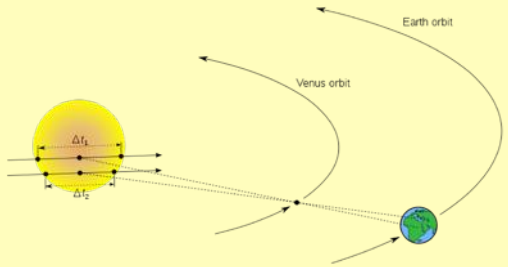


Venus (*June 6, 2012*)

Q: *Why was determination of AU such a big deal? (eg. though it was a time of war between many major powers they still worked together on this)*

- ***universe*** finally had an *accurate* "scale"!

- notion of *distant objects* (***ie.*** *stars*) **reasonable** given *size of AU & distance to the planets*



CLICKER*: Determining the* ***astronomical unit*** *using planetary transits required…*

(a) accurately known viewing positions
(b) precise timing of the transit's duration
(c) non-trivial mathematics (geometry)
(d) all of the above

Discovery of Uranus

• for *thousands of years*, *6 planets*:
Mercury, ***Venus***, ***Earth***, ***Mars***, ***Jupiter***, ***Saturn***

Q: *Why were these the only known planets?*

• ***Neptune*** (& ***Pluto***) are too faint for ***naked eye***

• ***Uranus*** *barely* visible; *magnitude 6*, *~ 4 arcsec*
(eg) *Like viewing a golf ball from 1 km away*

William Herschel
(1738-1822)

• ***German*** born but lived in ***England***

• studied ***astronomy***

• built his own (***large***!) ***telescope***

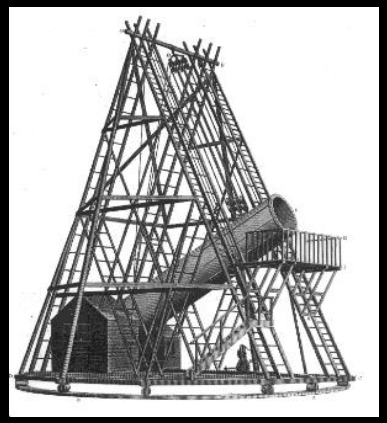
• discovered ***Uranus*** in ***1781***

• *wanted* to name it *"**Georgium Sidus**"*

Q: Uranus *is bright enough to see and had even been plotted as a star on skycharts in the 1600's - so why was it* ***not*** *identified earlier as a planet?*

• ***Uranus*** moves ***too slowly*** - only ***~ 4° per year***

Herschel's 48", 40 foot telescope

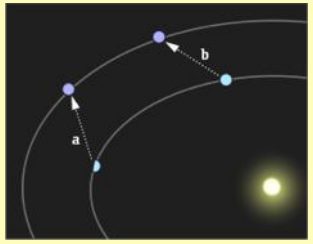


Discovery of Neptune

• early **1800's**: clear that ***Uranus***' orbit was *"off"*

• unlike *most other planets' positions*, which were **well predicted** using ***Newton's*** *Law of Gravitation*, ***Uranus***' *position grew less accurate over time*

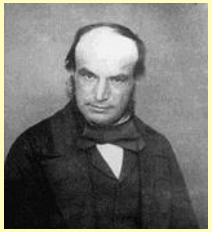
Q: *Why might this occur?*



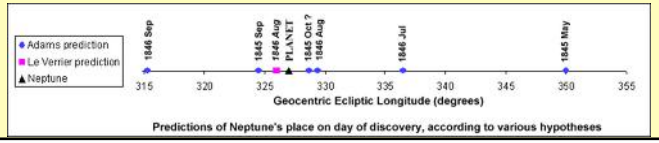
• some believed *gravitation* ***failed*** far from ***Sun***

• most thought ***another object*** pulled on ***Uranus***

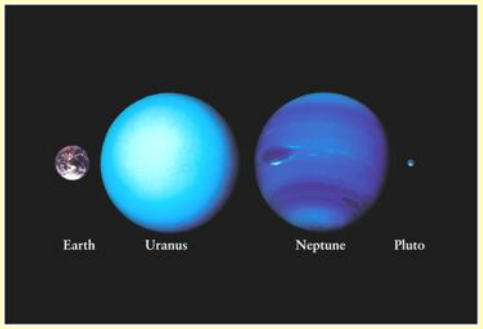
John Adams
(1819-1892)



- ***English*** mathematician
- calculated orbit of "*perturbing*" planet starting in1843, then 1845-46
- ***didn't publish***
- ***English*** astronomers searched *unsuccessfully*:
  - *starcharts* out of date (***misidentified*** *Neptune!*)
  - ***Adams***' calculations were off (***by up to 12º!***)



Predictions of Neptune's place on day of discovery, according to various hypotheses



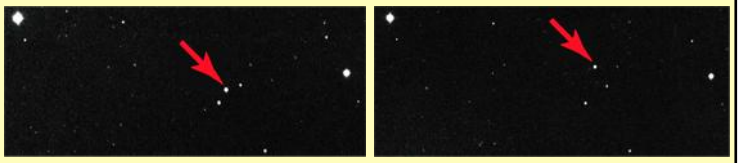
- ***Neptune*** is ***tiny*** from Earth: *magnitude 8, ~ 2"*
- ***Galileo*** may have seen it in his ***telescope*** in ***1613***, but it would have been *dim & moved very slowly*

Joseph Le Verrier
(1811-1877)

- ***French*** astronomer
- ***predicted*** a new planet in ***1846*** *mathematically*
- ***Gottfried Galle*** at *Berlin Observatory* searched…
- …and found ***Neptune*** **as predicted** after just ***an hour search the first night***! (up-to-date star charts)
- despite ***earlier*** prediction & ***correct*** mathematics, *discovery of* ***Neptune*** *shared with Adams*
- spurred by success, analyzed orbit of ***Mercury***
- attributed its motions to another planet: ***Vulcan***

Discovery of Pluto

- "*perturbations*" in ***Neptune's*** orbit - "***Planet X***"?
- discovered *1930* by *Clyde Tombaugh* in ***photos***



(photos 3 days apart; Pluto moved < 1 arcminute)

- orbits Sun *once every 250 years* (***~1.5º per year***)
- *~1000x* ***dimmer*** than ***naked eye*** can see!

"Backyard" Pluto

Pluto & Charon (HST)

Pluto (*July, 2015*)

Proof of Earth's Motions

- just because *we were not **able** to easily see things* (***Uranus***, ***Neptune***) *did **not** mean they weren't there*
- ***did*** the ***Earth really*** move (***rotate*** & ***revolve***)?

DEMO: *Galileo **argues** for a moving Earth…*

Q: *Why was this a **crucial** issue to resolve? Why were **Newton's** & **Kepler's** laws **NOT** enough?*

- ***science demanded*** (direct) *evidence*!

Galileo & a moving Earth

• *inertia! "… an object in motion…"*

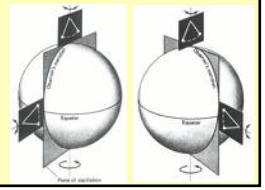
Earth's Rotation

• ***surprisingly difficult*** to **prove** ***Earth rotates***

• ***Jean Foucault (1851): Foucault's Pendulum***

• ***only force*** on a swinging ***pendulum*** is ***gravity*** – which is **vertical**! *What makes it "turn" then?*

• *swinging pendulum* **maintains** direction of swing *relative to stars* but **appears** to *change direction* as the ***Earth*** *rotates beneath it!*

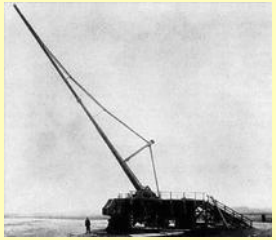


Foucault Pendulum

• *as Earth turns beneath it, pendulum knocks over objects spaced around a circle*

• ***Gustave Coriolis (1835)*** described **motion** of objects within a *rotating frame of reference*

• ***Germans*** in ***WWI*** noticed when shooting at Paris from ~100 km away they *did* ***NOT*** *hit what they aimed at****!***

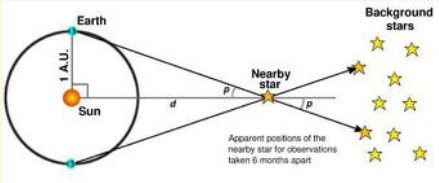


DEMO*: throw a ball while spinning. How do you see it move compared to class?*

(eg) *contrary to popular belief, direction water swirls down the toilet is NOT due to Coriolis Effect*

Revolution of Earth

• ***Friedrich Bessel (1838): parallax*** of ***61 Cygni***



• ***parallax = 0.3 arcseconds ⇒ ~11 ly away***
NOTE: 1 ly ~ 63,000 AU ~ 10 trillion km (!)

• **all** stars' ***parallax*** <1 ***arcsecond ⇒ >3 ly away***

• ***stars*** must be "***Sun-like***" to be visible from *so far*

Size of the Milky Way

• most thought ***our galaxy*** **was** the ***universe!***

• ***Newton*** & ***many*** others believed the ***universe*** **must** be *eternal, infinite* & *static*

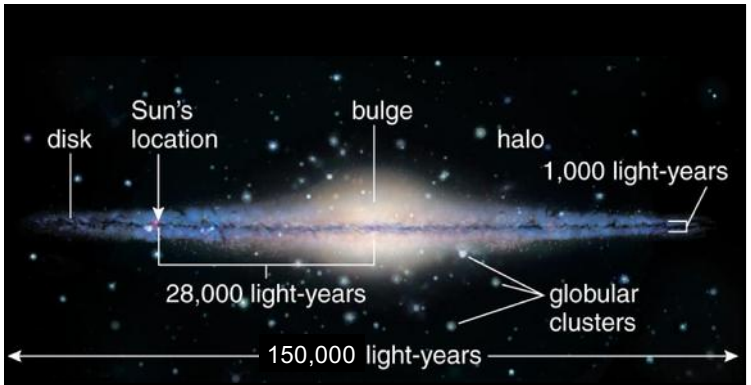
Q: *What would happen if universe was* ***finite****?*

Q: *Side-effect of an* ***infinite*** *universe… ?*

• philosopher ***Immanuel Kant*** (***1755***) & others proposed ***Milky Way*** was an "***island universe***"

• what ***are*** our ***galaxy*** & ***universe*** really like?

The Milky Way

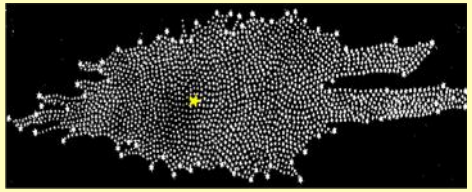


• ~150,000 ly across, disk ~1000 ly thick
• contains ~ ***100+ billion stars***

• ***Milky Way*** is a ***galaxy*** (“***galactos***”- *milk*), a grouping of ***gravitationally bound*** *stars & gas*

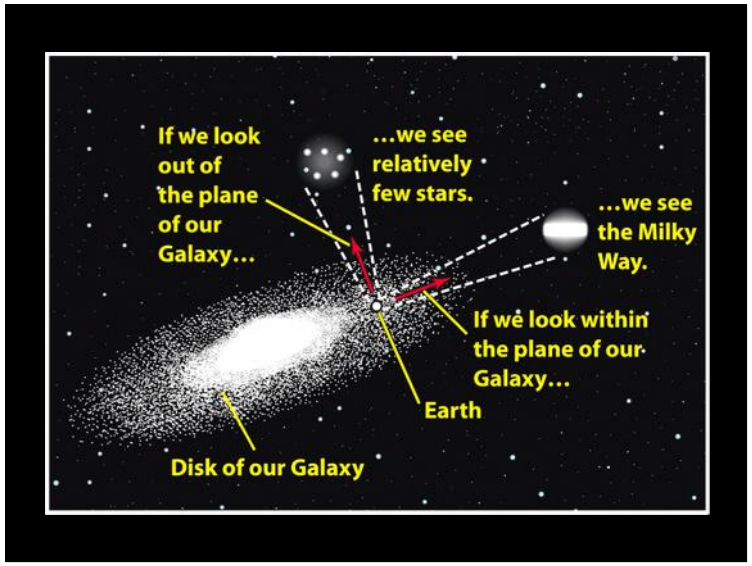
• ***Herschel*** “counted” stars *of* ***disk*** in all directions
• density *appeared* **uniform** - ***Sun*** *centered* !?!?!?

Q: *Why were astronomers skeptical of this result?*

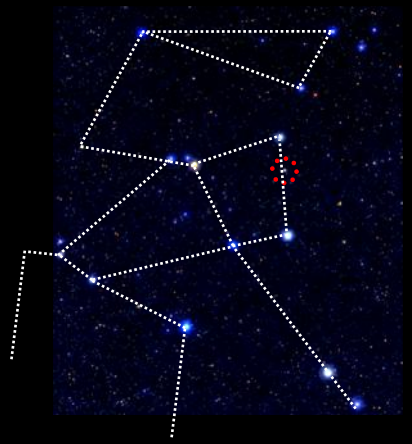


• ***Harlow Shapley*** observed ***globular clusters*** ***(1918)***

• *located above/below* ***disk*** - **not** obscured by dust!



Hercules & M13



Globular Cluster M13

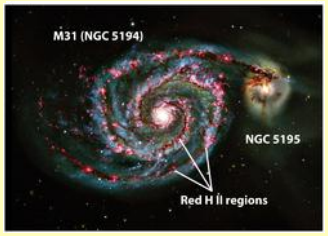
• assumed these "*balls of stars*" orbit ***galactic core***

Q: *Why was this a reasonable assumption?*

DEMO: *Starry Night Pro: Globular distribution*

• clearly **not** ***Sun*** *centered!*

• what about "fuzzy patches" - so-called ***spiral nebulae***?



• ***Shapley*** believed they were close, "*like*" ***globulars***

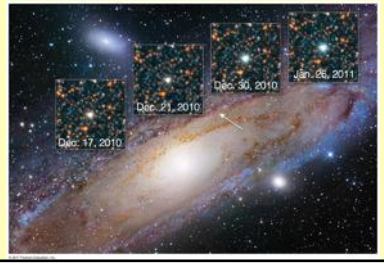
• others took ***Kant's*** view of "***island universes***"

Q: *Why did this "debate" go nowhere?*

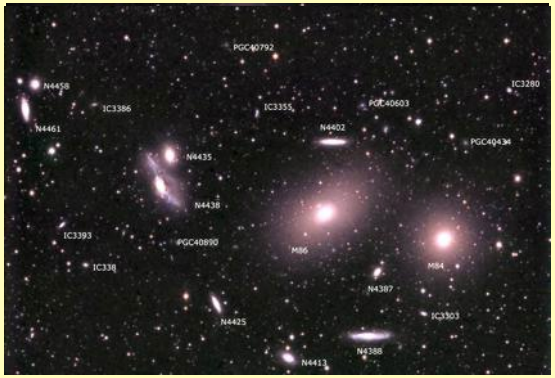
• ***Hubble*** observed ***Andromeda Nebula*** (***1923***)

• pulsating ***Cepheids*** indicated ***Andromeda 2.5 million ly*** away!

DEMO: *flashlight vs intensity*



• we were *one of many* "***island universes***"



Q: *Why did this idea meet with some resistance?*

• how *important* did ***Earth*** seem ***now***?

CLICKER*: Earth's location in the Milky Way is best described as…?*

(a) far above the "disk" of the galaxy
(b) close to the center
(c) about half way between the center & edge
(d) near the visible edge