Read Chapters 1 + 2 :

1. universe [L. unus (one) + vertere (to turn)] The totality of all things

Discuss : universe + Universe

Universe : Mysterious + unknown. Will it ever be known?
universe : models of Universe ; present knowledge of the universe.

2. Cosmology : Study of the models of the universe.

What is it all about?
Why did it all begin?
How will it all end?
What is the meaning of life?

Is cosmology a science?

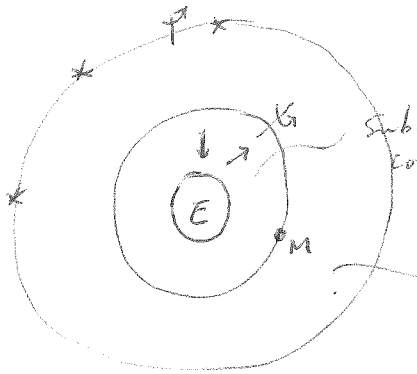
Give a detailed discussion of astronomy as a science, astology, etc.

Ancient Cosmic Systems:

- The Magic Universe — magic < Gr. magikos of the Magi (mysterious power)
- The Mythic Universe
- The Anthropocentric Universe
  - Human beings at the cosmic center!
  - Developed into Aristotelian Cosmology (accepted by the Church)

    Aristotle : 4th century B.C. (384 - 322 B.C.)

Studied in Plato's Academy, but later founded his own school called the Lyceum (the peripatetic school)
: lectured while walking around with students.



sublunar realm containing the Earth (non-rotating sphere)

celestial realm containing the planets (Moon, Mercury, Venus, Sun, Mars, Jupiter, Saturn)

attached to translucent spheres that rotated around the Earth.

56 supporting spheres were needed to explain the motions of planets + stars.

- Terrestrial elements: earth, water, air, fire
  composed the Earth and inner sublunar sphere

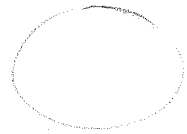
- ether (later also known as quintessence) composed the outer celestial spheres.

Natural Motion: Terrestrial elements — up and down as they seek to find their proper place according to weight

Etheric Element: endless revolution around the Earth.

Motion: poorly understood, continual application of force necessary: applied force = resistance × speed.

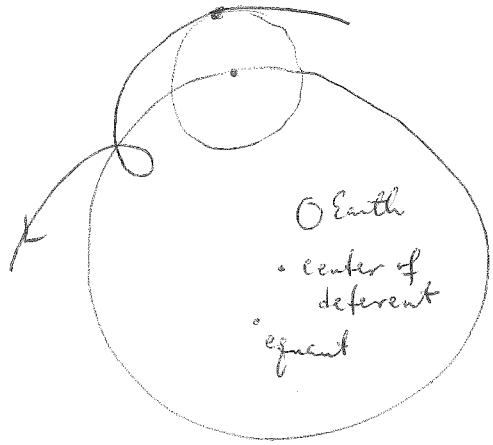
Aristotle's system: spatially finite, steady state
its perfect motions had no beginning or end



- Claudius Ptolemy 2nd century AD (Museum of Alexandria, Egypt)

astronomer + mathematician: Motion of planets in a geocentric universe

principal work:
Almagest
(The Great System)
(L. magnus: great)



{ eccentrics
epicycles
equants

- Nicolaus Copernicus (1473 - 1543) Catholic priest

work: Revolutions of the Celestial Spheres: 1543 shortly before his death

Heliocentric Universe: Earth rotates and revolves around the Sun in a circle. He dreamed of discarding the equants and restoring the original ideal of perfect circular motion.

- Tycho Brahe (1546 - 1601): Danish astronomer

Observed the motion of planets with the utmost precision possible before the introduction of telescopes.

His system: Earth at rest; Sun revolves around Earth, but planets revolve around Sun. (Tychonic System)

Johannes Kepler (1571 - 1630)

Imperial mathematician of the Holy Roman Empire, inherited Tycho Brahe's careful observations (previous imperial mathematician) and formulated 3 laws of elliptical planetary motion. Foundation stones in the Newtonian world system.

Galileo Galilei (1564 - 1642) — birth of Newton

birth of Shakespeare

Opposed physics of Aristotle, astronomy of Ptolemy

Supported Copernicus

Did experiments

Improved the telescope: mountains on the surface of Moon
satellites of Jupiter
numerous stars of the Milky Way

1610: The Starry Messenger

Conflict with Church: recanted under threat of torture the heliocentric system

Still believed in circular motion as the natural motion!

$x = vt$ uniform speed

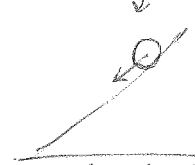
Impetus (Momentum) $= mv$

$$\begin{cases} v = at \\ x = \frac{1}{2}at^2 \end{cases}$$ uniform acceleration

measure time: human pulse, jet of water
- pendulum clock

Acceleration of Gravity Does not Depend upon Weight

impetus is conserved for a freely moving body



balls rolling down inclined planes

- The laws of physics apply everywhere; Earth is not the center of the Universe; Cosmological Principle!

René Descartes (1596 - 1650) French philosopher + Mathematician

Cartesian System: Mathematization of physical Sciences
Mechanical world View: Matter + Motion
Duality of body and mind

Infinite God
Clockwork Universe: Universe of Natural Laws --
- Matter of varying density suffused every part of indefinitely extended space; Everything behaved in accordance with reason.
- No atoms, no vacuum
- forces act by direct contact (pressure, tension)
- I think, therefore I am. Age of Reason (the Enlightenment) of 18th century!

Christiaan Huygens (1629 - 1695)

Dutch physicist + astronomer

improved design: telescopes Saturn's rings
pendulum clock

Circular motion $\frac{v^2}{r}$ = acceleration toward center
centripetal acceleration

Descartes + Huygens: gravity is a force caused by vortical pressure!

The Newtonian World System: Isaac Newton (1642 - 1726)

Robert Hooke, Christopher Wren and Edmund Halley

outlined qualitatively what Newton later explained quantitatively.

Dynamic theories of Motion and Universal Gravitation!
Invention of Calculus: Newton + Gottfried Leibniz (German mathematician + philosopher)

Book: Mathematical Principles of Natural philosophy (in Latin)
"Principia" 1687 : Absolute Space, Absolute Time

Laws of Motion: (i) $p = mv$ const. for free particle
(ii) $F = \frac{d}{dt}p = ma$
(iii) $F_{12} = -F_{21}$

Universal Gravitation: $F = G\frac{mm'}{r^2}$.

Ch. 4

One looks up and sees : stars
Milky Way , via lactea, Galaxy
nebulae nebula : "cloud"

Immanuel Kant (1724 - 1804)
Pierre S. de Laplace (1749 - 1827) : formation of solar system — rotating and contracting cloud of gas

The Nebula Hypothesis : interstellar gas clouds condense to produce solar systems

Speed of Light — Ole Roemer : 1676 studied motion of Io (a Galilean moon of Jupiter) and explained problems by finite speed of light

$c = 300{,}000$ km / sec

Sun - Earth distance 500 sec (8 min) =
AU = astronomical unit
$= 1.5 \times 10^{13}$ cm

$$\frac{1.5 \times 10^{13} \text{ cm}}{3 \times 10^{10} \text{ cm/sec}} = \frac{1}{2} \times 10^{3} \text{ sec} = 500 \text{ sec}$$

Spectroscopy — Study of colors
frequency of light , wavelength of light

$$\text{frequency} = \frac{c}{\text{wavelength}}$$

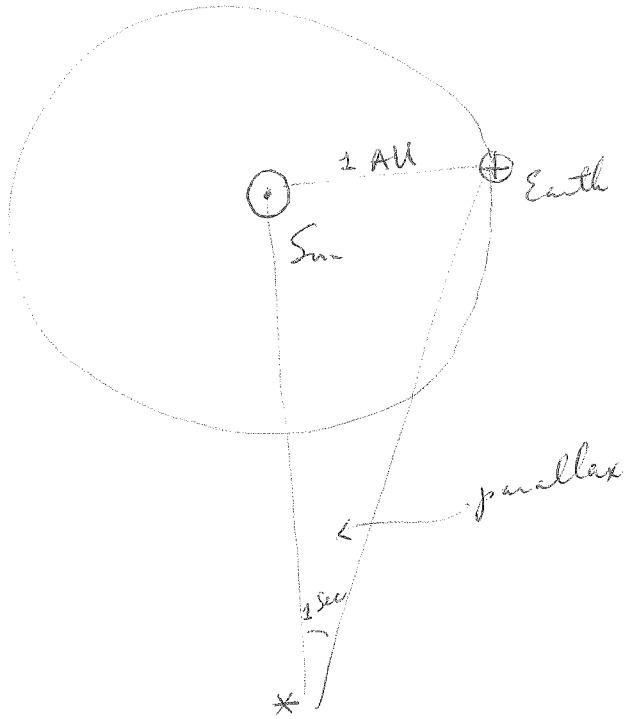
Doppler Effect — Christian Doppler, (Austrian)
Armand Fizeau (French)

1842 : Doppler effect for sound
1848 : for light / stars' colors change due to their motion

Victorian Universe (19th century) :
one-island universe : solar system at center of Galaxy (the mainland of the universe) — beyond it was a great void.

Ch. 5 (Stars) The Sun is a typical star!

parallax : apparent change in the position of an object resulting from a change in the viewer's position



$$\frac{1\ \text{AU}}{1\ \text{parsec}} = 1\ \text{arcsec}$$

$$1\ \text{parsec (pc)} = \frac{1.5\times10^{13}\ \text{cm}}{\frac{2\pi}{360\times60\times60}}$$

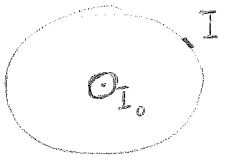
$$= \frac{(1.5)(3.6)^2}{2\pi}\times10^{18}\ \text{cm} = 3.26\ \text{lyr}.$$

Scale of Distances: Use light travel time

Distance to the stars:

- Stellar parallax can be measured up to ~ 300 lyrs
- After that one uses intrinsic brightness / apparent brightness.

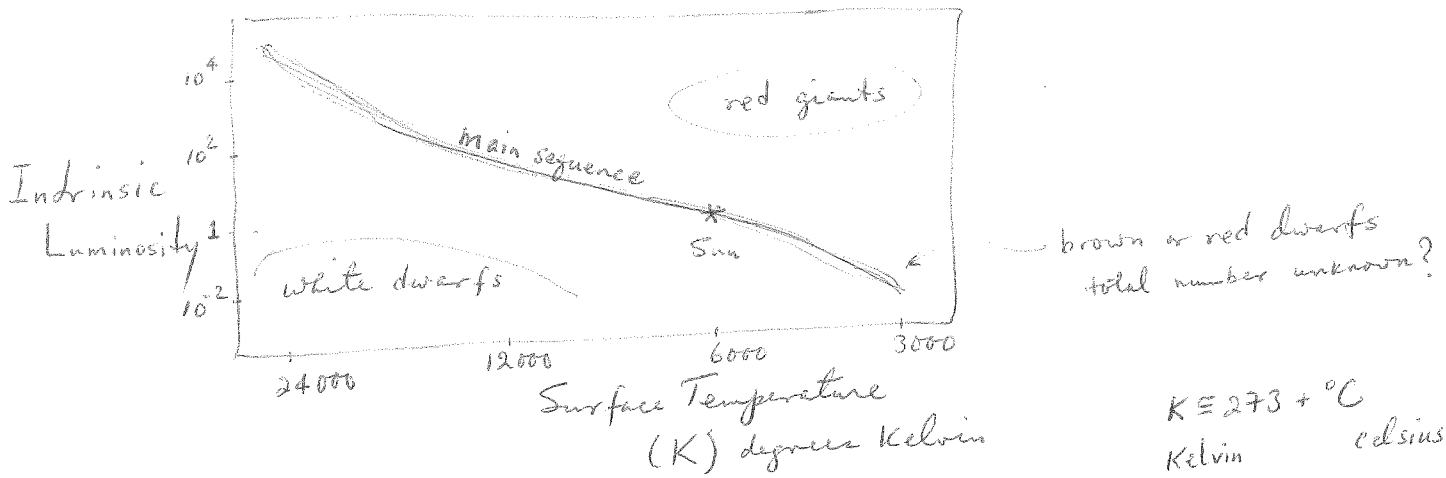
$$\text{Apparent Brightness} = \frac{\text{Intrinsic Brightness}}{4\pi r^2}$$



$$I = \frac{I_0}{4\pi r^2}.$$

- Half of all stars are members of binary or multiple star systems.

- Hertzsprung - Russell (H-R) diagram:



- $L_\odot$ = solar luminosity $= 4 \times 10^{33}$ ergs/sec $= 4 \times 10^{20}$ megawatts

  $M_\odot$ = mass of the Sun $= 2 \times 10^{33}$ gr

  $R_\odot$ = radius of Sun $= 7 \times 10^{10}$ cm

- A star on the main sequence generates its energy by slowly converting hydrogen into helium.

  $0.1 M_\odot \rightarrow 10^2 M_\odot$; radius of most luminous / radius of least luminous ~ 25

- Red giants : distended globes of cool gas with extremely large surface areas.

- white dwarfs : about the size of the Earth, extremely dense + hot

  dying stars : 10% of nearby stars are white dwarfs.

- Variable Stars :

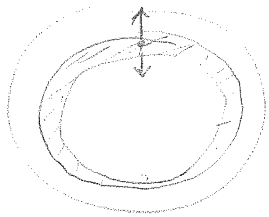
  25% eclipsing binary systems

  75% pulsating variables (expanding + contracting with a definite period)

  - Important class of pulsating variables are cepheids -- they are distance indicators.
    - first discovered in constellation Cepheus
    - over 700 cepheids are known in our Galaxy period 3 - 50 days brightness changes by factor 5
    - luminous yellow giants above the main sequence
    - Henrietta Leavitt (1912, Harvard College Observatory) discovered period - luminosity relation

Energy:

- Stars are globes of hot gas that radiate energy away into space.
- pressure of the gas balances the attraction of gravity



- $4\,{}^1H \rightarrow {}^4He + 25\ MeV$ fusion Nuclear Burning

  $E = Mc^2$: efficiency <u>0.008</u> release of energy due to fusion

- Birth of Stars:

  universe fragmented into galaxies

  galaxies fragmented into stars

  Solar system was born ~ 5×10^9 yrs ago.

  blob of gas → protostar (~75% H, ~25% He, ~1-2% heavier elements)

- Hydrogen exhaustion – End of Nuclear Burning

Massive Stars: White Dwarfs

Supernovas, Neutron Stars

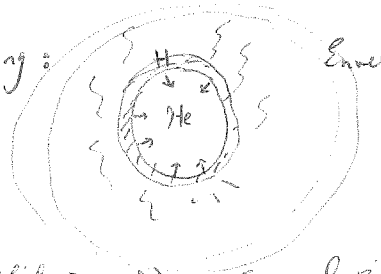
Black Holes

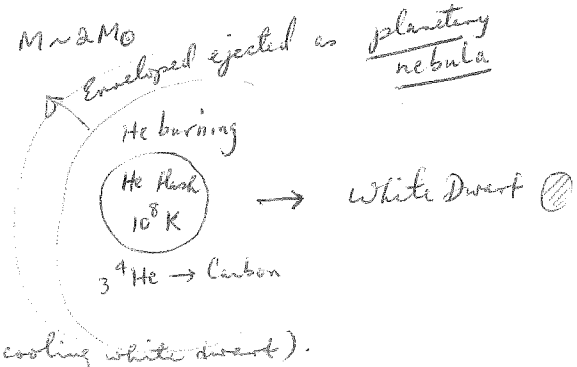
Low-Mass Stars: They evolve very slowly and take longer than 10×10^9 yrs to go through nuclear burning. Many have not evolved appreciably in the lifetime of the galaxy.

Massive Stars:

End of Hydrogen Burning:

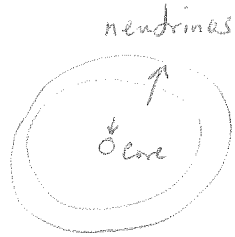
↳ Red Giant phase





Sun → 5 Billion yrs (White Dwarf) → Several Billion yrs (cooling white dwarf).

Supernovas:

$M \gtrsim 3M_\odot$ Star $\xrightarrow[\text{Several million yrs}]{}$ Red Giant $\longrightarrow$ 

Supernova Explosion
Luminosity $\sim 10^{11} L_\odot$

Neutron Star

$R \sim 10$ Km

Density of nuclear matter $\sim 10^{15}$ gm/cm^3

$3M_\odot \gtrsim M \gtrsim M_\odot$

Neutron Stars: pulsars ($B \sim 10^{12}$ gauss) — Crab Nebula, Crab pulsar (rotates 33 times a second).

Recorded Explosion 1054 AD in China.

Perhaps once every hundred yrs in our Galaxy!

Neutron Star: "ululates across space a pulselike message of matter stressed to its uttermost limit"

End of Nuclear Burning $\longrightarrow {}^{56}Fe$; heavy elements are ejected into space in the envelopes; new stars form with planets made from the heavy elements.

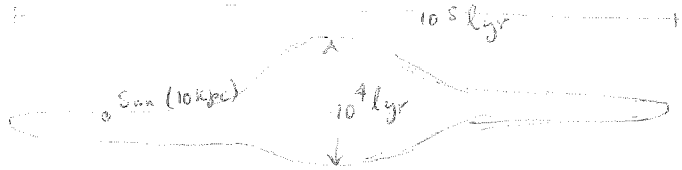
Black Holes: Mass of collapsed object $\gtrsim 3M_\odot$.

Do we understand everything about stars?

(i) solar neutrino puzzle?

(ii) fate of massive stars? Black Holes?

Ch. 6 – Galaxies



Our Galaxy : Disk + Halo (~200000 lyr)

Disk : Population I stars, young, have planets, rich in heavy elements, rich in dust and gas
10% gas ; 1% dust

Halo : Population II stars, old (8–15 $\times 10^9$ yrs), no planets, poor in heavy elements,
poor in dust + gas

Globular Clusters (~100 – 200)

Star clusters – Open clusters
globular clusters

– Open clusters : exist in the disk, [aggregations of young population I stars
~100 or several hundred
pleiades cluster (p. 101, "seven sisters")

– Globular clusters : halo + nucleus bulge, spherical,
diameter ~100 lyr, ~10^5 population II (very old) ~15×10^9 yrs

Both clusters are important for distance measurements : H-R diagrams for different clusters can be compared. If H-R diagram is 4 times fainter, it is 2 times more distant.
Nearest open cluster is Hyades (~150 lyrs, ~200 stars, in Taurus)
p. 390 – we compare the others with Hyades.

Nebulae : clouds of gas and dust
Gas clouds : Reflection Nebulae (reflect light from nearby stars)
Emission Nebulae (heated by nearby or embedded stars)
Obscuration : small grains of matter, dust, 1–2% of mass
Disk : intensity of starlight → 1/2 every 3000 lyr in the disk
Need for infrared and radio waves to look at galactic center.

Motion of Sun in the galaxy / Nature of Galactic Center / Sagittarius A-West ~10^6 M⊙ Black Hole

Ellipticals and Spirals —

Elliptical galaxies — contain very little gas or dust, old Population II stars
Wide range of sizes + masses
dwarf galaxies → supergiant galaxies
$\sim 10^{13} M_\odot$, 500,000 lyr

Giant ellipticals are usually E0 (spherical, bright nuclei)
dwarf ellipticals ~ globular clusters, no bright nuclei

Spiral galaxies — disk (population I), halo (population II)
spiral arms coiled around nuclear bulge

Normal spirals S : Sa, Sb, Sc Sb : our Galaxy + Andromeda
Barred spirals SB : SBa, SBb, SBc
No great ranges in masses + sizes $10^{10} - 10^{12} M_\odot$

Irregulars — "Irr" 10% of all galaxies Small + Large Magellanic Clouds

Describe Tuning fork diagram of Hubble.

Clusters of Galaxies :
Regular ; spherical 10^7 lyr in diameter ; thousands of galaxies
ellipticals + S0
Irregular : all kinds
Local Group (~ 20 galaxies)
Coma cluster (450 mlyr from us) hundreds of galaxies
Virgo cluster (70 mlyr from us) thousands of galaxies

Local Supercluster : Virgo Supercluster (center in Virgo cluster)

Distances : Use brightest stars in galaxies, cepheids, as distance indicators.

Radio Galaxies, QSOs (quasars), AGNs, Black Holes (Massive)
1931, Karl Jansky (Bell Labs) : radio signals from Milky Way

- Radio Galaxies : usually giant ellipticals, emit much more energy in radio than in optical regime

radio jets Electrons moving in magnetic fields = synchrotron radiation

Taurus A : Crab Nebula
Cygnus A : 3C 405 both extended + compact

- Quasi-Stellar Objects (QSOs) : 3C 273 strong radio source, star-like in optical appearance

1963 Maarten Schmidt : $z = 0.16 \approx \frac{v}{c}$ for 3C 273 → extragalactic

Allan Sandage : Many QSOs are radio quiet. Quasi-Stellar : Quasar – all starlike objects of large redshift (regardless of radio activity).

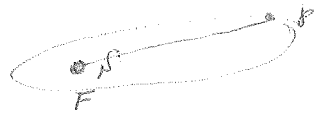
- Seyfert galaxies = giant spirals with an active galactic nucleus AGN

AGNs : Supermassive Black Holes

- Flat Rotation Curves :

Kepler's Laws : (1) planet moves around sun in an ellipse

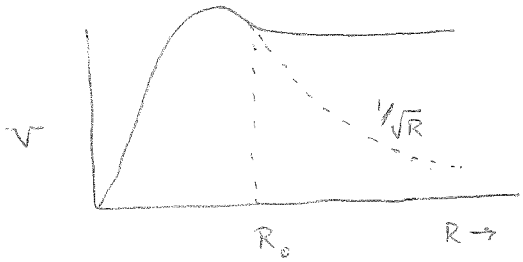
(2) PS line sweeps out equal areas in equal intervals of time



(3) $\frac{4\pi^2}{T^2} = \frac{GM}{R^3}$ R = average distance, T = period

Conclude $V = \frac{2\pi R}{T} = \frac{2\pi R\sqrt{GM}}{2\pi R^{3/2}} = \frac{\sqrt{GM}}{\sqrt{R}}$!

Spiral Galaxy :



See page 391 of Harrison's textbook!

$R_0 \simeq 30{,}000$ lyr

Dark Matter Problem! Luminous Matter is only 10% or less of the total mass.

Answer : MACHOS (Massive Compact Halo Objects) : brown dwarfs, red dwarfs, black holes

Very few have been found, not enough! Dark Matter ?

Ch. 7 – Location and the Cosmic Center

Location principle: It is unlikely that we have special location in the universe! If we do, we do not know about it.

– Isotropy of the Universe: The universe is almost isotropic about us.

– Cosmic Microwave Background Radiation CMBR, CBR

1965 Arno Penzias and Robert Wilson

$T_{\text{max intensity}} \simeq 2.728$ K $\lambda = 1$ millimeter

~ 400 photons / cm^3

– Average density of matter in our galaxy ~ 1 H/cm^3 (one atom of Hydrogen)

– Average density of matter in universe 10^{-6} H/cm^3.

$$\frac{\delta T}{T} \sim \frac{\delta}{1000} \sim \frac{v}{c}$$

Dipole anisotropy: we are moving at 600 km/sec in the direction of constellation Leo

Motion:

Earth rotation $v = \frac{2\pi R}{T}$

$v_{eq} = \frac{2\pi \times 6400}{24 \times 60 \times 60} \approx 0.5$ km/sec

Earth – Sun 30 km/sec

Sun – Galaxy 300 km/sec

Galaxy – Local Group (Andromeda) 100 km/sec

Local Group – Local Supercluster (Virgo cluster) 330 km/sec

Local Supercluster – Hydra – Centaurus supercluster 310 km/sec

Quadrupole Anisotropy: $< 10^{-5}$ imprint of perturbations that evolved into galaxies....

– The Cosmological Principle: On the largest scales, the space is homogeneous, i.e. all places are alike.

In a homogeneous universe, if one place is isotropic, then all other places must be isotropic.

– Observed Isotropy + Location Principle $\Rightarrow$ Homogeneity of Space

Ch. 8 – "Containment principle": the physical universe contains everything that is physical and nothing else.

Heaven! consciousness!

-- The universe contains space and time and does not exist in space and time.

dynamics of space and time in general relativity!

-- The cosmic-edge riddle -- What happens if we keep going on a straight line?

Expanding

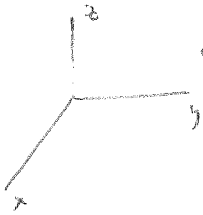
Atomists + Epicureans: Space was infinite in extent with no edge, endlessly populated with stars, etc. This leads to the Riddle of a Dark Night-sky!

Aristotelians: Sphere of Fixed Stars is the edge of the universe.

Neoplatonic and medieval – gradual ending of space: as one moved away from Earth, the physical realm transformed into an etheric realm (surrounded by the empyrean, realm of God).

Stoic cosmic edge – finite cosmos of stars surrounded by an infinite starless void.

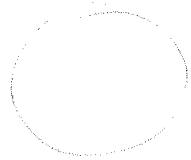
This was Isaac Newton's view in his early years at Cambridge.



Euclidean 3-space

centerless + edgeless infinite universe

;



Sphere:
2-space
centerless +
edgeless

Hubble Expansion: Space between galaxies expands – galaxies are at rest in space!

Design Argument: The universe is intentionally designed to be a fit place for human habitation. (Deism)

Theistic Principle: Why is the universe the way it is? Because God made it that way for the benefit of life.

Anthropic Principle: The universe is the way it is because we exist. (Dicke, Carter, etc.)

-- Why e, G, ħ, c have the values they do? Why electrons have same charge?

- Idea of Many Universes ; Variation of fundamental constants
- Internal and External Relations :

  Geoffrey Chew : Nature is as it is because this is the only possible nature consistent with itself.

  Berkeley, Mach, Einstein, ... : The inertia of a body is determined by the distribution and masses of all other bodies in the universe.

Brief Review of Physics :

Newton — Mechanics { point particles m
absolute space and time

Maxwell — Electricity + Magnetism (Optics)

Electromagnetic Wave : Ether's undulations

Motion : point particles, EM waves

Planck — Quantum Theory
wave - particle duality

Forces of Nature
{ Gravitation , Electromagnetism
Weak Nuclear Interaction Strong Interaction

Ch. 9 Space and Time

Space : dressed and undressed

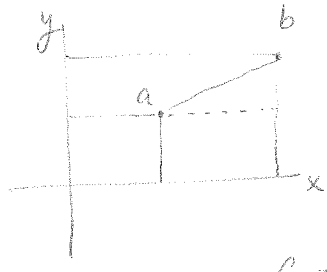
Dressed:
Aristotle, René Descartes .... ether ("fifth" element)

James Clerk Maxwell

Undressed : Atomists of the ancient world
Newton

absolute space, relative space

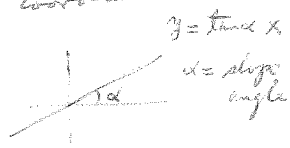
Descartes : algebra + geometry

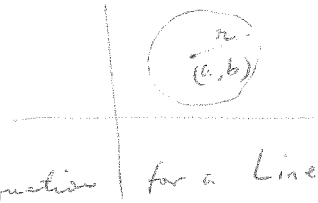


-- $(\text{distance } a \leftrightarrow b)^2 = (x_b - x_a)^2 + (y_b - y_a)^2$

-- Equation of a circle

(x, y) : Cartesian coordinates





$(x-a)^2 + (y-b)^2 = r^2$

$y = -\frac{A}{B}x + \frac{C}{B}$

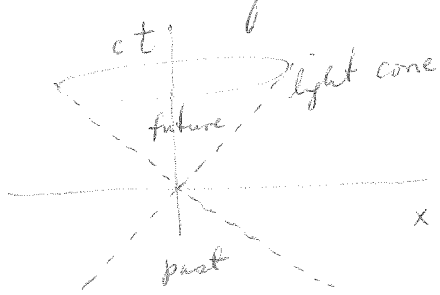
-- Equation for a Line : $Ax + By = C$

-- Equation for the surface of a sphere : $(x-a)^2 + (y-b)^2 + (z-c)^2 = r^2$.

points inside a sphere : $(x-a)^2 + (y-b)^2 + (z-c)^2 < r^2$.

Time : physical (atomic, cosmological, thermodynamic)
biological
psychological

Time as the fourth dimension : Hinton 1887 ; Minkowski ~1907



-- The Arrow of Time
-- Time Machine ; Time Travel

- Quantization of time and space

- Planck time, length, mass

L, T, M (classical physics: Laws remain invariant under scale change)
Q

Not true in quantum theory! Planck : $\hbar$

Planck Length $\left(\frac{\hbar G}{c^3}\right)^{1/2} = L_P \simeq 10^{-33}$ cm

Planck Time $= \frac{L_P}{c} = T_P \simeq 3\times10^{-44}$ sec $\left(\frac{\hbar G}{c^5}\right)^{1/2}$

Planck Energy $= \frac{\hbar}{T_P} = \frac{\hbar c}{L_P} = \frac{\hbar c}{\left(\frac{\hbar G}{c^3}\right)^{1/2}} = \left(\frac{\hbar c^5}{G}\right)^{1/2} \simeq \frac{10^{-27}\times 3\times10^{10}}{10^{-33}} \simeq 3\times10^{16}$ erg

$= \frac{3\times10^{16}}{1.6\times10^{-12}} \approx 2\times10^{28}$ eV $\Rightarrow \frac{3\times10^{16}}{(3\times10^{10})^2} \simeq 3\times10^{-5}$ gm

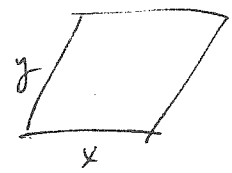
$\sim 10^{19}$ GeV

(Ch. 10, 11, 12)

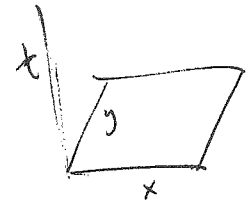
Ch. 10 – Geometry

$$\Delta l^2 = \Delta x^2 + \Delta y^2 + \Delta z^2$$

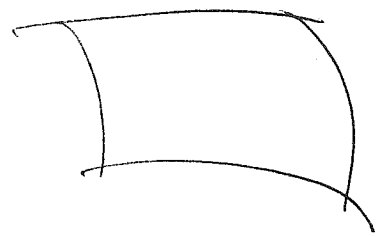
Euclidean Space

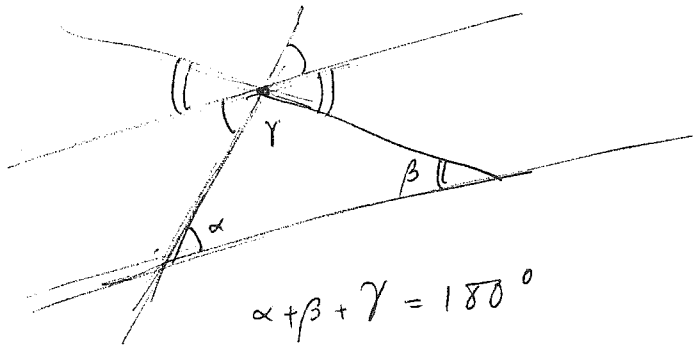


Spacetime $\quad \Delta s^2 = -\Delta t^2 + \Delta l^2$

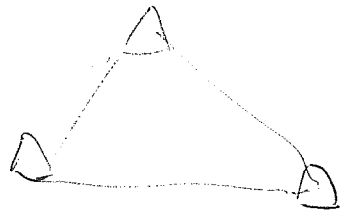


Curved Spacetime $\quad \Delta s^2 = -f(t,\underset{\sim}{x})\,\Delta t^2 + g(t,x)\,\Delta x^2 + k(t,x)\,\Delta t\,\Delta x + \dots$





$\alpha + \beta + \gamma = 180^\circ$

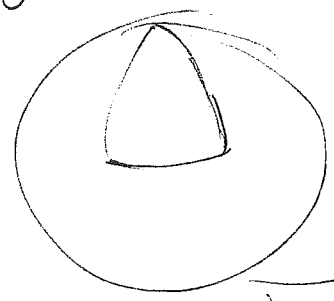


Gauss: Let us measure this!
(1777 – 1855)

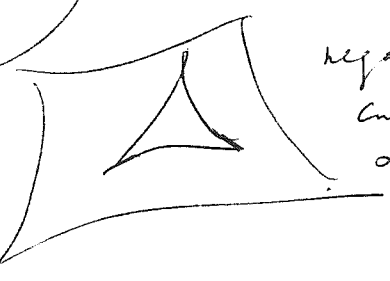
Developed geometry of curved surfaces.

$(\alpha + \beta + \gamma - 180^\circ = K \cdot \text{area of triangle})$ spherical space

K = curvature



positive curvature
$\alpha + \beta + \gamma > 180^\circ$



negative curvature
$\alpha + \beta + \gamma < 180^\circ$

hyperbolic space

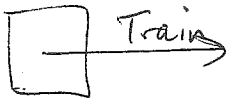
Riemann: student of Gauss
(1826 – 1866)

generalized work of Gauss to arbitrary dimensions.

Riemann, Clifford speculated that geometry of world is curved.

ch. 11 - Relativity

Galileo, Newton

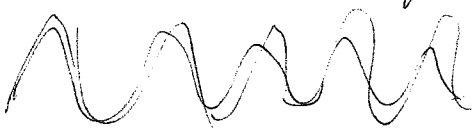


Station

$$\left.\begin{aligned} t &= t' \\ x &= x' + vt \end{aligned}\right\}$$

Galilean invariance
principle of Relativity

E+M Maxwell
E-field, B-field



electromagnetic waves

Light is Electromagnetic Radiation.

Optics had to be explained using E+M waves.

<u>Aberration of Starlight</u>

Ole Roemer 1676 : $c = 3 \times 10^{10}$ cm/sec

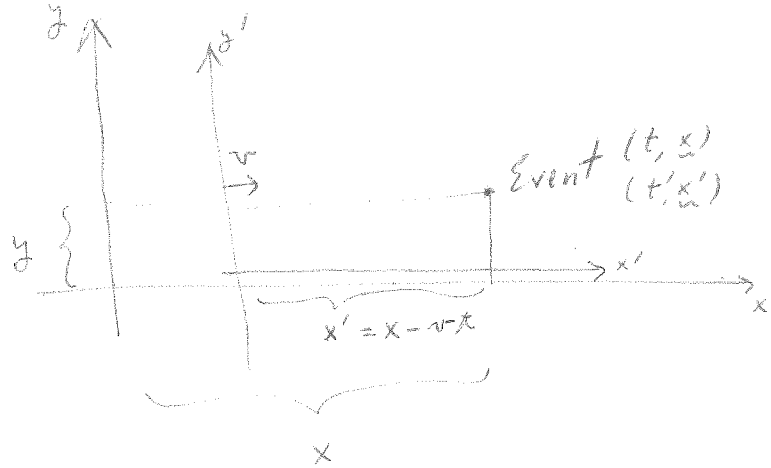
James Bradley — 1729

discovered aberration of light : finite speed of light was finally accepted.

He used Newton's model of light : particle picture
Maxwell : wave picture (E+M)

Problem : Waves (E+M) could not explain aberration using Galilean invariance.

Galilean Transformation
$$\begin{cases} t' = t \\ x' = x - vt \end{cases}$$



Lorentz Transformation
$$\begin{cases} t' = t - \dfrac{xv}{c^2} \\ x' = x - vt \end{cases}$$

Length Contraction : $L = L'\sqrt{1-\frac{v^2}{c^2}}$

Time Dilation $\tau = \dfrac{\tau'}{\sqrt{1-\frac{v^2}{c^2}}}$

Lorentz Transformation
$$\begin{cases} t' = \dfrac{1}{\sqrt{1-\frac{v^2}{c^2}}}\left(t - \dfrac{vx}{c^2}\right) \\ x' = \dfrac{1}{\sqrt{1-\frac{v^2}{c^2}}}\left(x - vt\right) \end{cases}$$

$v \to -v$
$$\begin{cases} t = \dfrac{1}{\sqrt{1-\frac{v^2}{c^2}}}\left(t' + \dfrac{vx'}{c^2}\right) \\ x = \dfrac{1}{\sqrt{1-\frac{v^2}{c^2}}}\left(x' + vt'\right) \end{cases}$$

Discuss History :

Ether does not take part in the motion of matter.

c = universal constant $\boxed{v \to c}$ impossible

Ch. 12 General Relativity

- Field Equations ; transitions to Newtonian gravity
  - Black Holes

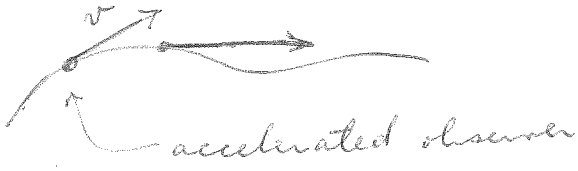
<u>Mach</u> : Relativity of All Motions

No Copernican Revolution!

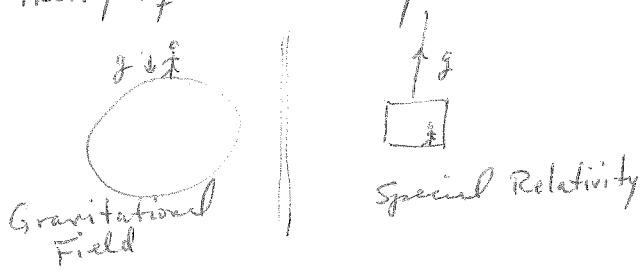
{ Inertial Forces must be due to the gravitational effects of distant masses.

Mach's Principle according to Einstein

Special Theory of Relativity : - Lorentz Transformations
- Hypothesis of Locality : apply Lorentz transformations point by point!



General Theory of Relativity : - Einstein's Principle of Equivalence : Locally, gravitational field is the same as an accelerated system in special relativity (i.e. flat Minkowski spacetime).



Two main consequences : - Light is deflected by gravity — bending of light rays

- Gravitational Redshift or Blueshift

Ch. 13 Black Holes —

- Formation : stellar size + massive black holes
  Oppenheimer et al.
- Properties —

Discuss Energy $E = \frac{1}{2} m v^2 - \frac{G m M}{r}$

Escape velocity $E \geq 0 \Rightarrow v \geq v_{esc} = \sqrt{\frac{2GM}{r}}$

Earth : $v_{esc} = 11.2$ km/s

Sun : " 618 km/s

Moon : 2.38 km/sec

Neutron Star : 2×10^5 km/s

Compare Aircraft + Shuttle speeds!

John Mitchell + Pierre de Laplace :

$$r \geq \frac{2GM}{c^2} \simeq \left(\frac{M}{M_\odot}\right) 3 \text{ km}$$

- Schwarzschild Radius, Gravitational Radius, Horizon

$$r_g = \frac{2GM}{c^2}$$

- Gravitational Redshift $\frac{\lambda_0 - \lambda}{\lambda} = \frac{1}{\sqrt{1 - \frac{R_s}{R}}} - 1$

- Rotating Black Holes
  Schwarzschild Black Holes
  Kerr Black Holes

- physics inside the horizon:

  roles of space + time reverses!

- physics of massive black holes

  tidal forces

  jets

Ch. 14 Hubble Expansion —

- Big Bang : A singularity — Naked singularities vs. Black Holes

- $\underset{\sim}{v} = H \underset{\sim}{r}$ Hubble Law : Consistent with Homogeneity and Isotropy

$\underset{\sim}{r} = R(t)\, \underset{\sim}{r_0}$; $H = \frac{\dot{R}}{R}$

Stretching a rubber sheet with galaxies spread on it homogeneously + isotropically.

-

$$\text{Energy} = \frac{1}{2} M v^2 - \frac{GM\left(\frac{4\pi}{3}\rho r^3\right)}{r}$$

$$\frac{\text{Energy}}{\text{Mass}} = \frac{1}{2} v^2 - \frac{4\pi}{3} G \rho r^2$$

$$= \frac{1}{2} H^2 r^2 - \frac{4\pi}{3} G \rho r^2$$

$$= \frac{1}{2} r^2 \left(H^2 - \frac{8\pi}{3} G \rho \right)$$

(i) Energy $= 0$, $\rho = \rho_{crit} = \frac{3H^2}{8\pi G}$

Space is <u>flat</u>, 3-dim Euclidean space Surface area of a sphere $= 4\pi r^2$

(ii) Energy < 0, $\rho > \rho_{crit} = \frac{3H^2}{8\pi G}$

Cloud is gravitationally bound.

Space is curved: Geometry of space is spherical. Volume is finite

Surface area of a sphere $< 4\pi r^2$

Universe expands to some max. radius + recontracts.

(iii) Energy > 0, $\rho < \rho_{crit} = \frac{3H^2}{8\pi G}$

Expands forever.

Space is curved: Geometry of space is hyperbolic. Volume is infinite.

Surface area of a sphere $> 4\pi r^2$.

In the three models, matter is decelerating.

- Observations show <u>acceleration</u> of the universe.

Cosmological constant : Λ

Repulsive cosmic force $= \frac{1}{3}\Lambda r$

Effective density of quintessence : $\frac{\Lambda}{8\pi G}$.

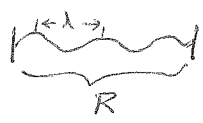
Density of Matter in the Universe:

Luminous matter

Dark matter

quintessence

Ch. 15 Cosmological Redshifts



λ expands as R : $\frac{\lambda_0}{\lambda} = \frac{R_0}{R}$

t_0 = present epoch

z = redshift

$$1+z = \frac{\lambda_0}{\lambda} = \frac{R_0}{R} \qquad z = \frac{\lambda_0 - \lambda}{\lambda} = \frac{R_0 - R}{R}$$

$z \sim 6 \Rightarrow$ radiation was emitted when the radius of the universe was $\frac{1}{7}$ of present radius.

$z \sim 10$ epoch of the formation of galaxies

$z \sim 1000$ decoupling era : The CMBR decouples from matter.

$z = \infty$ Big Bang

Darkness at Night – Why is the sky dark at night? Main reason: stars have finite lifetimes!