Revolutions in Science

A brief history of cosmology

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Cosmology: the study of the universe

- Is the universe finite?
  How big is it?

- Is the universe eternal?
  How old is it?

- How did the universe begin?
  How will it end?

- What is the nature of time?
  What is the nature of space?

Science or philosophy?
Useful Texts

• A Very Short Introduction to Cosmology
  *Peter Coles (OUP)*

• The Big Bang
  *Simon Singh*

• Cosmology
  *Edward Harrison (CUP)*

• The Cambridge Illustrated History of Astronomy
  *Michael Hoskin (CUP)*
Earliest cosmology

I. The age of magic
   Every that happened due to spirits

   - The anthropomorphic universe
     Fashioned in the image of mankind

II. The age of mythology
    Creation myths

   - The anthropocentric universe
     Spirits become remote Gods and Goddesses

   Sumerians, Assyrians, Babylonians, Minoans, Greek, Jews, Chinese, Norse, Celts, Mayans
Early mythology

Babylonians, Egyptians and Hebrews (6000 BC)

- Earth in the center of an oyster, covered by dome
- Water underneath and overhead, closed in on all sides
- Moderate dimensions
- Sun, moon and stars progress across dome
- Universe guided by deity, explained by myth
The Babylonian universe

The Hebrew universe
Earliest observations: astronomy

Chaldean priests (3800 BC)

- Timetables of the motion of the stars and the planets
- Stars stationary, planets move across a lane in the sky (zodiac)
- Length of the year
- Astronomy and astrology, calendars
- Predicted astronomical events

*Observation without explanation*
The Babylonians

- **Observations of the stars**
  
  *Nabonassar (747 BC)*

- **Calendar**
  
  *360 days = 1 year*
  
  *Lunar months: varied*

- **Measuring time**
  
  *The gnomon (sundial); 12 parts of the day*
  
  *1 hour = 60 minutes; 1 minute = 60 seconds*

- **Observations of the planets**
  
  - **The Zodiac**
  
  - **Circle on which the planets moved**
The cosmology of ancient Greece

**Ionian philosophers (6th cent BC)**
Natural causes: not concerned with deities

- **Thales of Miletos (625-547 BC)**
  What is the basic material of the Universe? Water
  Earth floats on water

- **Anaximander of Miletos (610-545 BC)**
  Raw material of universe: undefined *apeiron*
  Earth floats in universe infinite in time and space
  Mechanical model of the universe
  Estimated sizes and distances to sun and moon

- **Anaximenes of Miletos (585-528 BC)**
  Raw material: air. Earth floats on air
  Stars evolved from earth; float on sphere above
Pythagoras of Samos  (570-495 BC)

- Founder of science
- Mathematization of experience: numbers sacred and eternal
- Highest form of philosophy
- All things have form, all form defined by numbers

- Pitch of a note depends on the length of string that produces it
- Intervals in the scale produced by simple numeric ratios

- Reality could be reduced to number series and number ratios

Theorem: **Areas of the two smaller squares of the sides of right-angled triangle will equal the area of the larger square**
The Pythagorean universe

- **Earth is a sphere**
  
  *Ships on horizon*
  
  *Lunar eclipses*
  
  *Shape of moon and sun*

- **Orbits**
  
  *Sun, moon and planets revolve around central fire*
  
  *Each planet hums on a different pitch*
  
  *Intervals between orbits governed by laws of harmony*

- **Major influence**
  
  *Plato*
  
  *Kepler*
Downfall of the Pythagorans

* Discovery of irrational numbers
  * The diagonal of a square

* Arithmetic and geometry
  * Breakdown in point-to-point correspondence

* Tried to keep secret

* Dissolution of brotherhood
  * Also due to egalitarian practices, socialist society

* Pythagoras: founder of European culture, source of Platonism
## Legacy of Pythagorean School

- **Spherical earth**
  Attracts everything to its center

- **Aristarchus of Samos** (310 BC)
  "On the sizes and distances of the sun and moon"

- **Eratosthenes**
  Measured circumference of earth from summer solstice
  Deduced relative size of moon (from lunar eclipse)
  Deduced distance of moon from earth (from geometry)
  Deduced sun-earth/moon-earth distance (from half-moon)
  Deduced sun-earth distance
  Deduced relative size of sun (from solar eclipse)

\[
\frac{r_S}{d_S} = \frac{r_M}{d_M}
\]

Eratosthenes 276 – 195 BC
Philolaus and Aristarchus

- Earth sphere has motion: rotates about its own axis
- Daily revolution of the sky caused by earth's own motion
- Separated day and night, annual motion of the planets
- Earth orbits sun

First suggestion of heliocentric system

Quoted by Archimedes: yet heliocentric system was discarded

Aristarchus 310-230 BC
Plato and Aristotle

- Heroic age followed by decline
  
  *Should have been Aristarchus - Copernicus - Galileo*

- **Plato**: certainty in mathematics, not naturalism
  
  *Shape of the world must be a perfect sphere*
  *All motion perfect circles at uniform speed*

- Science dominated by **Aristotle** (logic and empiricism)
  
  *God spins the world from outside it, not from center*
  *Earth and moon space subject to change: nowhere else*
  *All celestial bodies orbit earth in perfect circles*

**Spherical universe rotates about spherical earth**
The dogma of Plato and Aristotle

- Planetary motion must be shown to be result of circular motions
  Aristotle: used 54 spheres to account for motion of the planets

- Ptolemy (AD 150): ultimate earth-centered model
  Complicated epicycle system for circular motion of celestial objects
  Ferris Wheel universe

- Tradition
  Enshrined in ‘He Magele Syntaxis’ ( later ‘The Almagest’)
  Kept alive by Islamic scholars during the middle ages
  Re-introduced to Europe in 1175 - 1600

- Dogma dismissed reality: 3 fundamental conceits
  Dualism of celestial and terrestrial motion
  Immobility of earth
  All heavenly motion perfectly circular
Why was Aristarchus universe discarded?

- Objects fall towards earth
- No wind blowing against us
- No obvious motion of stars
  (*stars too far away to observe stellar parallax*)
- Heliocentric model rejected
  *Geocentric model retained*
- One snag: motion of planets
  *Anomaly in paradigm*
Towards the Middle Ages

**Platonism** adopted by Christianity (St Augustine etc)

*Ignored early Greeks, adopted only Plato's philosophy: neoplatonism
11cent AD: same view as 5th cent BC*

**Medieval philosophy**

*Aristotle's 55 spheres, Ptolemy's 40 epicycles
Replaced by 10 revolving spheres: disregarded stellar observation
1000 AD: Portolano charts for navigation*

**12-16th century: Aristotelian philosophy adopted**

*Muslims: carried fragments of Euclid, Archimedes and Aristotle to Europe
Improved Calendric astronomy and planetary tables
Important Indian numerals (including zero) and algebra
Christianity and Aristotelianism (Thomas Aquinas)*

**Aquinas**: first proof of God (based on Aristotelian physics)
*Unmoved mover = God*
Summary

By 1500 AD, Europe ‘knew’ less than Archimedes in 200 BC

1. Splitting of Universe into 2 spheres
2. Geocentric dogma
3. Uniform motion in perfect circles dogma
4. Divorce of mathematics from science
5. Divorce of experiment from science

These 5 handicaps were to be overcome by
Copernicus, Kepler and Galileo
The Renaissance

- **Universities: Revival of learning**
  - Bologna, Paris, Oxford and Cambridge

- **Roger Bacon, William of Ockham and Albert the Great**
  - Study of nature: empiricism

- **Ockham’s razor**
  - Opposed Aquinas
  - “All other things equal, simpler explanation more likely”

- **Nicole d’Oresme**
  - Geocentric universe not proven

- **Nicholas of Cusa**
  - Earth not hub of universe

- **Nicolas Copernicus**

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Roger Bacon (1220-1292)

William of Ockham (1280-1349)
Nicolas Copernicus (1473-1543)

- Born in Poland (Prussia) in 1743
- Studied at the Universities of Krakow, Bologna and Padua
- Trained as Catholic canon
- Polyglot, polymath
- Simple instruments for observing the sky
- Used observations of the Chaldeans and the Greeks
- Improved astronomical tables
- Published *Commentariolus* (1514)
Nicolas Copernicus

Commentariolus (1514) : 7 axioms

1. Heavenly bodies do not share a common center
2. Earth is not the centre of the universe
3. Centre of the universe is near the sun
4. Earth’s distance to sun negligible compared to distance to stars
5. Daily motion of stars is due to rotation of the earth
6. Earth, planets revolve around sun
7. Retrograde motion of the planets is due to motion of earth

Distributed to friends, academics: became well-known

Earth cannot be stationary, Ptolemy system inconsistent
Heliocentric model (aware of early Greeks)
Nicolas Copernicus

*Book of the Revolutions of the Heavenly Spheres (1543)*

- Published with aid of Georg von Lauchen (Rheticus)
- Technical version of Commentariolus
- Ahead of its time (earth just a planet like others)

**Problems**

- Copernican system quite complicated (48 epicycles)
- Less accurate predictions of planetary motion
- Universe de-centralized: no natural center of directions
- Undermined by preface (Osiander)

Not adopted for many years: unnecessary, opposed by Church
2. Tycho de Brahe

Danish nobleman
Observational astronomy to new level
Own observatory on island of Hven
Expensive instruments: precise and continuous data

Observed distant nova (SN1572)
Observed distant comet (1577)
Heavens not immutable
Sympathetic to Copernican ideas
‘Mixed’ model of universe (1588)

Migrated to Prague (imperial mathematician)
Employed Kepler to study Mars
Gave data sparingly to Kepler
Died from drink (1600)
The Tychonian model

Observational astronomy to new level (own observatory)
Observations showed heavens not immutable

Sympathetic to Copernican ideas
Critical of Copernicus’s observations

Convinced of immobility of earth
Lack of stellar parallax v. sizes of stars
Aristotellean physics, religion

‘Mixed’ model of universe (1588)
Planets orbit sun
Sun and moon orbit earth

Geo-heliocentric model
Johannes Kepler

Born in Germany: not high-born
Mathematical prodigy
Attended University of Tubingen
Trained as Lutheran cleric
Became teacher of mathematics and astronomy in Graz

Defended Copernicus while still a young priest
*Mysterium Cosmographicum* (1596)
Reconciled Copernican model with scripture
First public commitment by astronomer to Copernican system
Platonic solid model of the cosmos

Hired by Tycho de Brahe (1600)
Given Mars project, but limited data
Not convinced by Tychonian model
Tycho dies after a few months
Johannes Kepler

Death of Tycho de Brahe
Kepler becomes Imperial Mathematicus (1601)
Access to all of Tycho’s data
Solves problem of the orbit of Mars (8 years)

Mars orbits sun in elliptical path
All planets move in elliptical paths: no epicycles
First accurate heliocentric model of universe
"Astronomia Nova " (1609)

Simple, elegant model
Natural laws: precise, verifiable statements based on data
Material bodies acted upon by forces
Accurate predictions

Ignored by Germans and Italians (incl. Galileo?)
Accepted by British (Thomas Harriot, Jeremiah Horrocks)
Kepler’s universe

Kepler’s planetary laws

1. Planets move in elliptical orbits (not circles)
2. Planets continuously vary their speed (not uniform)
3. Sun is at focus of ellipse (not center of circle)

Kepler’s other work: founded instrumental optics

*Optics* (1604)

Study of refraction by lenses
Light intensity $\alpha \frac{1}{r^2}$

Principle of sight, spectacles
Camera obscura
Studied pendulum as student
(period depends only on length)
Invented pendulum timing device

Appointed lecturer in mathematics at the University of Pisa (1589)
Chair of Mathematics at the University of Padua (1592)

Studied mechanics in detail
Laid foundations of dynamics
Laws of motion of falling bodies
Optics: lenses, mirrors and camera obscura

Relativity of motion
Ball drops independent of ship’s motion
Could earth be moving?
Galileo’s astronomy

Improved Dutch model of **telescope** (mag x 30)

Discovered Lunar surface not smooth (contradicts Ptolemy)

Discovered moons of Jupiter: earth not center of all things

Discovered phases of Venus (as predicted by Copernicus)

Discovered innumerable stars in Milky Way

Discovered sunspots: sun subject to decay etc

Defended Copernican system **Sidereus Nuncius** 1610

Measurements confirmed by Jesuits
University Aristotelians opposed Galileo

*Letter to Castelli/ Grand Duchess Christina*

Defended Copernican system, suggested scriptures not literal

Church Charges brought against Galileo in 1615, dropped

Church demanded proof of Copernican system

Galileo refused (couldn't prove): ignored Kepler's findings

Galileo censured by decree (1616): Copernican model outlawed
The Galileo Affair (II)

1623: New pope friendly towards Galileo

1632: "Dialogue on the Great World Systems"

Propounds Copernican system: pope cast as Simplicio

Pope displeased, felt deceived

1633: Galileo interrogated by Inquisition
Found guilty of defying 1616 decree
Sentence: House arrest for life: *Dialogue* prohibited

After trial
Magnum Opus – dynamics
*Dialogue Concerning Two New Sciences* (1636)
Born in Lincolnshire 1642
Promising student
Studied mathematics at Cambridge (TC)
Studies interrupted by Great Plague of 1666
Significant work at home in calculus, optics, gravitation

Gravitation theory synthesized what went before
1. Kepler's laws (planetary motion)
2. Galileo's laws (motion of bodies on earth)

What is nature of the force that drives the planets?
What will a body do if left alone?

Key step: *Identified Keplerian orbit of moon with Galilean orbit of projectile*
Newton’s Principia (1687):

Law 1 *Every body continues in its state of rest, or uniform motion in a straight line, unless compelled to change by forces acting on it*

Law 2: *The change in motion is proportional to the force impressed, and in the direction of the force*

Law 3: *To every action there is always an equal and opposite reaction: the mutual actions of two bodies upon each other are always equal, and directed to contrary parts*

Laws 6 and 7: *Universal Law of Gravitation* \( F_G = \frac{Gm_1m_2}{r^2} \)
Isaac Newton

Universal law of gravity (1666)
Force of attraction proportional to the masses,
Inversely proportional to square of separation

\[ F_G = \frac{GMm}{r^2} \]

Dropped for 20 years
Developed mechanics and calculus

Goaded back to problem by Halley
Computes force of earth's attraction for the moon (1686)
Explains observed motion: repeated for sun
Showed orbit produced by law was Kepler ellipse
Kepler's laws arise as consequence

Moon = falling body
Newton’s law of gravity

\[ F_G = \frac{GMm}{r^2} \quad G = \text{constant (6.6x 10^{-11})} \]

Unites terrestrial and celestial gravity
Force on apple = force on planets

\[ F_G \text{ v. weak force (G extremely small)} \]
\[ F_G \text{ only seen when one mass is a planet} \]
\[ F_G \text{ always attractive} \]
\[ M,m = \text{inertial mass (see N2)} \]

How does \( F_G \) act instantaneously across huge distances?

\[ F = \frac{Gm_1m_2}{r^2} \]
The Newtonian universe

1. Force of gravity –
   Attractive, weak, infinite range

2. Eternal universe (infinite in time)
   No beginning, no end

3. Bentley’s paradox
   Why doesn’t gravity crush universe?
   Finite mass in infinite space (Newton)

4. Olbers’ paradox
   Why is the sky dark at night?

Clockwork universe: space and time a fixed stage
Astronomy in the 19\textsuperscript{th} century

1. Improved telescopes
   \textit{Distances to stars}

2. Stellar parallax
   \textit{Bessel 1838}

3. Photography
   \textit{Improved images}

4. Spectroscopy
   \textit{Analysis of starlight}
   \textit{Spectral lines of known elements}
   \textit{Stars made of familiar elements}
The starry nebulae

Extremely distant, cloud-like formations
*Island universes?* Kant, Laplace

Study of the nebulae using large telescopes
*Herschel: 36-inch reflecting telescope*

Some nebulae have spiral structure
*Earl of Rosse (1845): 72-inch telescope, Birr castle*

Stars within spirals
*Earl of Rosse: Birr castle*

Distance to the nebulae?
*Too distant for parallax method*
The motion of the nebulae

Vesto Slipher

*Use of spectrograph to study nebulae*

*Lens speed of camera: Exposure time*

First study of the nebulae (Lowell Observatory)

*Light significantly blue-shifted (1912)*

*Doppler shift due to radial motion?*

*Approaching at 300 km/s*

**Redshift of the spiral nebulae**

*45 Doppler shifts (1917): all red-shifted except 4*

*Radial velocity outward? Large velocities: 300 to 1100 km/s*

**Conclusion**

*Distant nebulae moving away: most distant moving fastest*
The Doppler effect

Perceived frequency of light and sound depends on relative motion of observers

Measure motion of object by measuring shift in frequency of light emitted

Christian Doppler
1803-1853
The great debate

A new measurement of distance (Leavitt)
Pulsating stars: Cepheid variables (1912)
Intrinsic luminosity related to period of pulsation
Measure distance by measuring period of luminosity

Size of Milky Way (Shapley)
Use Leavitt’s law to measure Milky Way (0.5 MLY)
V bright nova in Andromeda: within Milky Way?

Nebulae outside Milky Way? (Curtis)
Emission lines Doppler-shifted: Vesto Slipher
Motion too great to be confined to Milky Way

Measurement of distance to nebulae (Hubble)
Well outside Milky Way
Hubble’s answer (1925)

- Edwin Hubble (1921)
- Ambitious astronomer

- Hooker telescope (Mt Wilson, 1917)
- 100-inch reflector

- Resolved Cepheid stars in nebulae
- Known luminosity and distance
- Far beyond Milky Way! (1925)

Nebulae are distinct galaxies
Hubble’s Law (1929)

- What do the velocities of the galaxies mean?
- Is there a relation between distance and velocity?
- Combine 24 distances with Slipher redshifts
- Approx linear relation: **Hubble’s law**

**Furthest galaxies receding fastest**

*Slipher not acknowledged*

\[ H = 585 \text{ km/s/Mpc} \]
Distances for 40 galaxies

Redshifts for 40 galaxies

Reduced scatter – linear relation

Justification

Hubble & Humason (1931)

Recession Velocity (km/sec)

Distance (Mpc)

Explanation?
The expanding universe

- What do the redshifts represent?
- Recession velocities for distant galaxies?
- If so, why?
- Newtonian gravity pulls in $F = GMm/r^2$
- What is pushing out?

Space, time fixed
Relativity

The principle of relativity
Laws of mechanics identical for observers in uniform motion
Non-accelerated motion

Galileo
Motion of ball in cabin of sailing ship
Impossible to deduce motion of ship

Application
Elizabeth I and the Irish Chieftains

Everyday experience
Cup of tea on train
Life on earth
Relativity in the 19th century

**Electromagnetism**

*Electricity and magnetism = electromagnetism*

*Speed of electromagnetic wave = speed of light*

**Light = an electromagnetic wave**

*Travelling wave*

*Changing electric and magnetic fields*

**The electromagnetic spectrum**

*From radio waves to X-rays*

**Speed of light absolute?**

*Fixed for all observers?*

*Micelson-Morley experiment*
Einstein’s special theory of relativity

Two new principles (1905)
Laws of physics the same for observers in uniform motion
Speed of light the same for observers in uniform motion

Implications
Distance and time not absolute \( v = s/t \)
Experienced differently by bodies in motion

Predictions for high-speed bodies
Length contraction; time dilation
Mass increase; equivalence of mass and energy \( E = mc^2 \)

Space + time = spacetime
Space-time invariant (Minkowski)
Evidence for special relativity

**Mass increase**

*The experiments of Kaufmann and Bucherer*

\[ m' = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}} \]

**Time dilation**

*The long-lived muon*

\[ t' = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}} \]

2 μs → 22 μs

**Invariance of the speed of light**

*Always measured as c*

**Particle experiments at the LHC**

*Maximum velocity = c*

*Mass increase*

*Particle creation*

\[ E = mc^2 \]
The general theory of relativity (1916)

- Extending the special theory (1907-)
  Relativity and accelerated motion?
  Relativity and gravity?

- The principle of equivalence
  Equivalence of gravity and acceleration

- Mach’s principle
  Inertial mass defined relative to matter
  Space and time defined by matter

- A long road (1907-1915)
  Curvilinear geometry, tensor algebra
  Gravity = curvature of space-time
The field equations of GR (1915)

\[ G_{\mu\nu} = - \kappa T_{\mu\nu} \]

10 non-linear differential equations that relate the geometry of spacetime to the density and flow of energy and momentum

**SR**

\[ ds^2 = dx^2 + dy^2 + dz^2 - c^2 dt^2 \]

\[ ds^2 = \sum_{\mu, \nu=1}^{4} n_{\mu\nu} dx^\mu dx^\nu \]

\[ n_{\mu\nu} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix} \]

**GR**

\[ ds^2 = \sum_{\mu, \nu=1}^{4} g_{\mu\nu} dx^\mu dx^\nu \]

\[ g_{\mu\nu} : \text{variables} \]
Three astronomical tests (Einstein, 1916)

- **Different in principle from Newton’s gravity**
  Small deviations in practice (weak scale)

- **The perihelion of Mercury**
  Well-known anomaly in Mercury’s orbit (43" per century)
  Postdicted by GR (1916)

- **The bending of starlight by the sun (1.7")**
  Eclipse expeditions of Eddington and Dyson (1919)
  Successful measurement (large error margin)

- **Gravitational redshift**
  Time dilation in strong gravitational field
  Light from a massive star redshifted?
Eclipse Results (1919)

Sobral: 1.98" +/- 0.16
Principe: 1.7" +/- 0.4

Asymmetric controversy (Collins and Pinch 1970s)
Claim of bias; rebutted by astronomers (RAS)

Einstein famous (1919)
Einstein’s universe

**Einstein: apply GR to the Universe (1917)**

*Ultimate test for new theory of gravitation*

**Assumptions**

*Static universe (small velocities of the stars)*

*Mach’s principle (metric tensor to vanish at infinity)*

*Isotropy and homogeneity (simplicity)*

**Boundary problem**

*Assume cosmos of closed curvature*

*But...no consistent solution*

**New term in field equations!**

*Cosmic constant - anti-gravity term*

*Radius and density defined by λ*

\[
G_{μν} = -κ \, T_{μν}
\]

\[
G_{μν} + λg_{μν} = -κ \, T_{μν}
\]

\[
λ = \frac{κρ}{2} = \frac{1}{R^2}
\]
Friedman’s universe

- **Allow time-varying solutions (1922)**
  - Assume homogeneity, isotropy, positive curvature
  - Two independent differential equations from GFE

- **Evolving universes**
  - Density of matter varies over time

- **Negative spatial curvature (1924)**
  - Cosmic evolution, geometry depends on matter

- **Overlooked by community**
  - Considered ‘suspicious’ by Einstein
  - Mathematical correction, later retracted
  - “To this a physical reality can hardly be ascribed”

\[
G_{\mu\nu} + \lambda g_{\mu\nu} = -\kappa T_{\mu\nu}
\]

\[
\frac{3R^2}{R^2} + \frac{3c^2}{R^2} - \lambda = \kappa c^2 \rho,
\]

\[
\frac{R^2}{R^2} + 2R\frac{R''}{R} + \frac{c^2}{R^2} - \lambda = 0.
\]

Alexander Friedman (1888 -1925)
Lemaître’s universe (1927)

- Expanding model of the cosmos from GR
  Similar but not identical to Friedman 1922

- Redshifts of galaxies = expansion of space?
  Redshifts from Slipher, distances from Hubble

- Ignored by community
  Belgian journal (in French)
  Rejected by Einstein: “Vôtre physique est abominable”

- Lemaître’s recollection (1958)
  “Einstein not up-to-date with astronomy”
The watershed: Hubble’s law (1929)

- The redshifts of the spiral nebulae
  Doppler shifts? (Slipher 1915, 1917)

- The distances to the nebulae
  Far beyond Milky Way (Hubble 1925)

- A redshift/distance relation
  Linear relation (Hubble, 1929)
  \[ H = 500 \text{ km s}^{-1} \text{ Mpc}^{-1} \]

- Landmark result in astronomy
  Furthest galaxies receding the fastest

  Link to relativity
The expanding universe (1930)

- **RAS meeting** (May 1930)
  
  *If redshifts are velocities, and if effect is non-local*
  
  *Hubble’s law = expansion of space? (Edd., de Sitter)*

- **Dynamic model required**
  
  *Static model unstable*

- **Lemaître model adopted**
  
  *1927 expanding model republished in English (1931)*
  
  *Observational section omitted (rightly)*

- **Lemaître-Friedman cosmology accepted**
  
  *Time-varying radius, decreasing density of matter*
Who discovered the expanding universe?

- Einstein: Basic framework for theory
- Friedman: Expanding universe (theoretical)
- Hubble, Slipher: Recession of the galaxies (obs)
- Lemaitre: Observation + theory

‘Hubble graph’ should be Hubble-Slipher graph
‘Hubble expansion should be Hubble-Lemaitre expansion

Astronomers sceptical (Hubble)
Models of the expanding universe (1930 -)

- **Tolman** (1930, 31)
  
  *Expansion caused by annihilation of matter?*

- **Eddington** (1930, 31)
  
  *On the instability of the Einstein universe*
  
  *Expansion caused by condensation?*

- **de Sitter** (1930, 31)
  
  *Variety of expanding models*

- **Heckmann** (1931,32)
  
  *Spatial curvature (not translated)*

- **Einstein** (1931, 32)

  *Friedman-Einstein model*  \( \lambda = 0, \ k = 1 \)
  
  *Einstein-de Sitter model*  \( \lambda = 0, \ k = 0 \)
A strange prediction: the big bang

- **Lemaître 1931**: expanding $U$ smaller in the past

- **Extrapolate** to very early epochs

- Extremely dense, extremely hot

- Expanding and cooling ever since

- ‘Fireworks beginning’ at $R = 0$?

Rejected by community (1930-60)

*Simplified models*

*Timescale problem*

Later called ‘**The big bang**’
A second line of evidence

Gamow and nuclear physics (1940s)
Student of Friedman

How were the chemical elements formed?
Problems with stellar nucleosynthesis

Elements formed in the infant hot universe?
Theory predicts $U = 75\%$ Hydrogen, $25\%$ Helium

Agreement with observation
Victory for big bang model

Heavier atoms formed in stars
Bonus: cosmic background radiation

- Infant universe very hot
- Dominated by radiation
- Radiation still observable today?  
  *Low temp, microwave frequency*
- A fossil from the early universe!  
  *Released when atoms formed (300,000 yr)*

**No-one looked**

*Alpher, Gamow and Herman*
The steady-state universe (1948)

- **Expanding but unchanging universe**
  - Hoyle, Bondi and Gold (1948)
  - Disliked extrapolation to early epochs
  - **Perfect cosmological principle?**

- **Requires continuous creation of matter**
  - Very little matter required
  - No beginning, no age paradox

- **Replace \( \lambda \) with creation term (Hoyle)**
  \[ G_{\mu\nu} + C_{\mu\nu} = -k T_{\mu\nu} \]

- **Improved version (1962)**
  \[ G_{\mu\nu} + \lambda g_{\mu\nu} = k T (C_\mu + C_\nu) \]
Steady-state vs big bang (1950-70)

- **Optical astronomy (1950s)**
  - Revised distances to the nebulae (Baade, Sandage)
  - New timescale of expansion

- **Radio-astronomy (1960s)**
  - Galaxy distributions at different epochs
  - Cambridge 3C Survey (Ryle)

- **Nucleosynthesis of light elements**
  - Gamow et al. 1948

- **Cosmic microwave background (1965)**
  - Low temperature, low frequency
  - Remnant of young, hot universe
Cosmic background radiation (exp)

**CMB discovered accidentally**

- Universal signal (1965)
- Low frequency (microwave)
- Low temperature (3K)

*Echo of Big Bang!*

*Penzias and Wilson (1965)*
The big bang – evidence

1. The expansion of the $U$
2. The abundance of $H$ and $He$
3. The distribution of the galaxies
4. The cosmic microwave background

*How did it start?*
Astronomical search for cosmic parameters

Density of matter, rate of expansion

The search for two numbers

\[ H_0, \Omega_M \]

\[ q_0 = \frac{\Omega_M}{2} \]

Hypothesis of dark matter

Dynamics of galaxy rotation

Some matter seen only by its gravitational effect

Problems

Density of matter too small to close universe

But no evidence of spatial curvature!
Modern measurements of the CMB

• Details of background radiation
• Full spectrum
• Comparison with theory
• Perturbations?

• *Ground telescopes*
• *Balloon experiments*
• *Satellite experiments*

*COBE satellite (1992)*
Cosmic background radiation

- Expected temperature
- Expected frequency
- Perfect blackbody spectrum

- radiation too uniform?
- perturbations $< 1 \text{ in } 10^5$?
- galaxy formation?

COBE (1992)

*Nobel Prize 2006*
Problems

Background radiation raised new questions

- **Horizon problem**  *why so uniform?*
- **Galaxy problem**  *how did galaxies form?*
- **Flatness problem**  *fine balance?*

Conflict between theory and experiment

Astrophysics: $\Omega = 0.3$
Dark Matter

- First suggested in 1930s
- Stellar motion

*normal gravitational effect but cannot be seen directly*

- Explains motion of stars
- Explains motion of galaxies
- Explains gravitational lensing

\[
\text{Matter} = \text{OM} \ (20\%) \ + \ \text{DM} \ (80\%)
\]

\[
\Omega = 0.3 \ ?
\]
The horizon problem

• Two distant regions of microwave background have similar temps

  Why?

  Too far apart to be causally connected

  • Finite speed of light
  • Finite age of cosmos

Something wrong with lookback
Galaxy formation problem

- Microwave background smooth on large scale
- No deviations from homogeneity obvious (1 in 10,000)
- How did slight perturbations become galaxies?
The flatness problem

Slightest deviation from flatness → runaway expansion or crunch

Not observed

Why so finely balanced initially?

Astrophysics: $\Omega = 0.3$?
The Theory of Inflation (1981)

- Initial **exponential expansion**
- Driven by *phase transition*

**Repulsive force**

- Expansion of $10^{35}$ in $10^{-32}$ s
- Smooths out inhomogeneities
- Smooths out curvature

*’No hair’ universe*
The inflationary universe

- Solves horizon problem
  *Early U incredibly small*

- Solves flatness problem
  *Geometry driven towards flatness*

- Mechanism for galaxy formation
  *Quantum fluctuations inflated*

\[ \Omega = 1 ? \]

*Conflict between theorists and experimentalists*

- Einstein-de Sitter: $\lambda = 0, k = 0$

- Flatness prediction (Dicke, inflation)
  
  $k = 0$

- But: $\Omega_M = 0.3$

- But: new timescale problem from HST
  
  $H = 87 \text{ km s}^{-1} \text{ Mpc}^{-1} : t = 11.2 \times 10^9 \text{ yr}$

  too young

  *Is model wrong? Is $\lambda \neq 0$?*
The accelerating universe (1998)

- Supernovae as standard candles (1998)
- Furthest galaxies too far away
- Expansion accelerating
- **Implies repulsive energy**  
  *Dark Energy* ($\lambda \neq 0$)
- Possible support for inflation ($\Omega = 1?$)
The flat universe (2000)

- Balloon measurements of CMB
- The BOOMERANG experiment
- The MAXIMA experiment

- Geometry is flat ($\Omega = 1$)

  Implies dark energy component

  $$\Omega_M + \Omega_\Lambda = 1 \quad (\Omega_\Lambda = 0.7)$$

- Support for inflation
WMAP Satellite (2002)

- Details of $CMB$ spectrum
- Details of galaxy formation
- Details of flatness of $U$
- Details of dark energy

Cosmic microwave background
WMAP measurements of CMB (2005)

- Spectrum of $T$ variations
- Geometry is flat (to 1%)
- Dark energy 74%

**Strong support for dark energy**

**Strong support for inflation**

Fit to theory
Modern big bang model: $\Lambda$-$CDM$

A flat, accelerating universe containing matter, dark matter and dark energy

1. Ordinary matter: 4% (astrophysics)

2. Dark matter: 22% (astrophysics)

3. Dark energy: 74% (supernova, CMB)

$\Omega = 1$
Cause of acceleration: dark energy

- Predicted by relativity
- Cosmological constant
- Natural tendency of space to expand

- Energy of vacuum?
- Why so small?
- Why of similar density to matter?

- Not well understood
- Fate of universe?
New results: Planck Satellite (ESA, 2013)

1. Improved sensitivity
   \[ \frac{\Delta T}{T} \approx 1 \times 10^{-6} \]

2. Full spectrum of T anisotropy
   New acoustic peaks: scale invariance?
   Accurate values for \( \Omega_\Lambda, \Omega_M \)

3. Gravitational lensing
   Remove degeneracies

4. Polarization measurements
   E-modes: fluctuations
   B-modes: gravity waves?
Planck Satellite (ESA): Results

COBE

WMAP

Planck
Planck results (2013)

1. New Hubble constant
   \[ 67.3 \pm 1.2 \text{ km/s/MPC} \]
   \[ \text{Age} = 13.8 \text{ billion yr} \]

2. Curvature; flat
   \[ \Omega_k = -0.0005 \pm 0.07 \]

3. New mass/energy parameters
   \[ \Omega_\Lambda = 68, \; \Omega_{DM} = 27, \; \Omega_{OM} = 4.9 \% \]
The big bang - problems

- Nature of dark energy?  
  *Role in BB?*

- Which model of inflation?  
  *The multiverse?*

- The singularity problem
  *What banged?*  
  *What does time zero mean?*  
  *No-boundary universe*
The singularity: a cyclic universe?

- Breakdown at time zero
- No model of bang itself
- Multiple bangs?
- Colliding branes
- Prediction of string theory

- Cyclic universe
- Eternal universe

*Tests? Non-Gaussianities in CMB*
The big bang – evidence

1. The expansion of the $U$

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How did it start?
The big bang model
Today’s cosmological puzzles

- **Characteristics of background radiation**
  *Isotropy, homogeneity, flatness (1970-80)*

- **The theory of inflation (1981)**
  *Exponential expansion within first second?*
  *Explanation for homogeneity, flatness, galaxy formation*
  *Which model of inflation? Bubble inflation?*

- **Dark energy (1998)**
  *Observation of accelerated expansion*
  *The return of the cosmological constant*
  *U mainly composed of dark energy*
  \[ G_{\mu\nu} + \lambda g_{\mu\nu} = -\kappa T_{\mu\nu} \]
  *Nature of DE unknown*